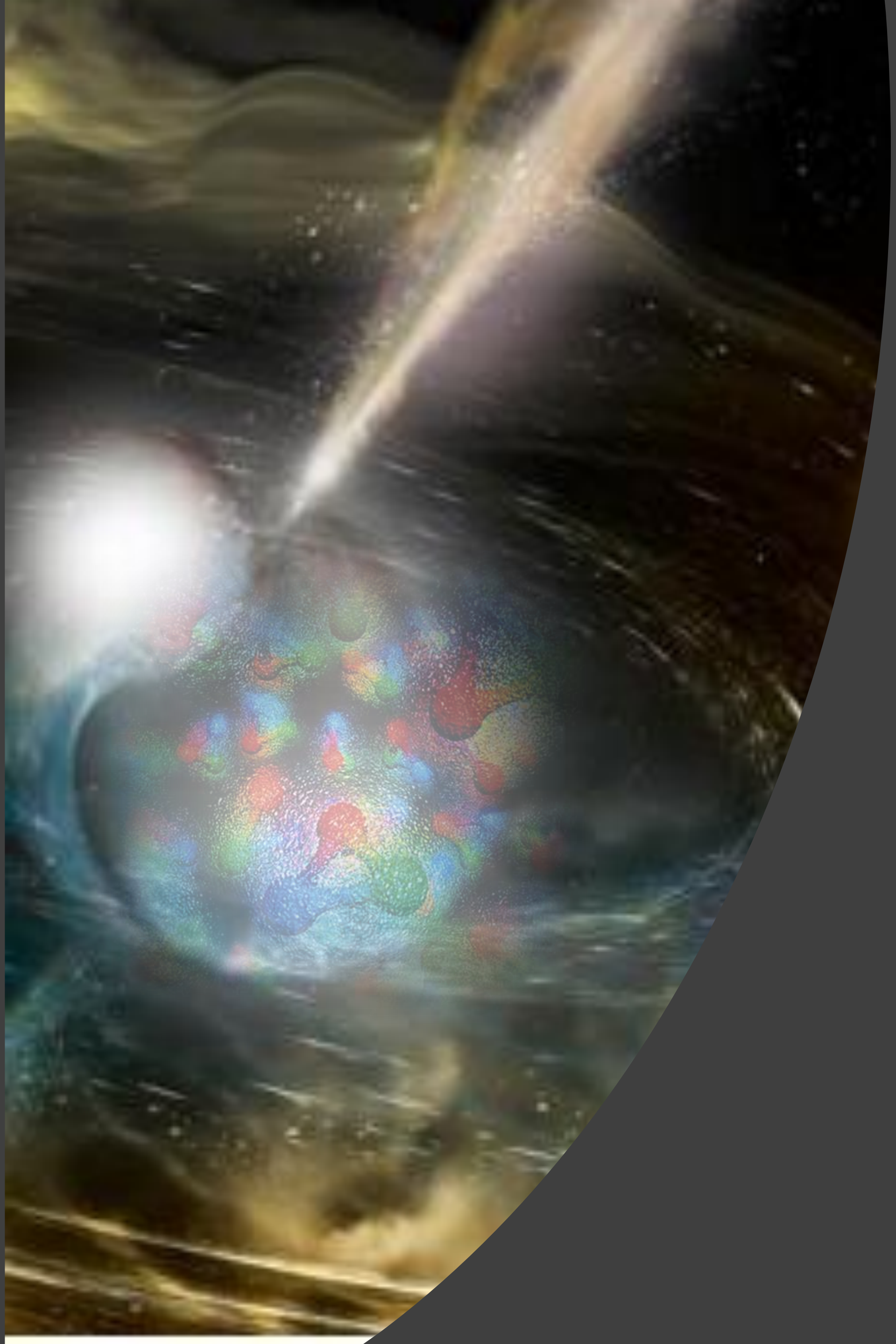
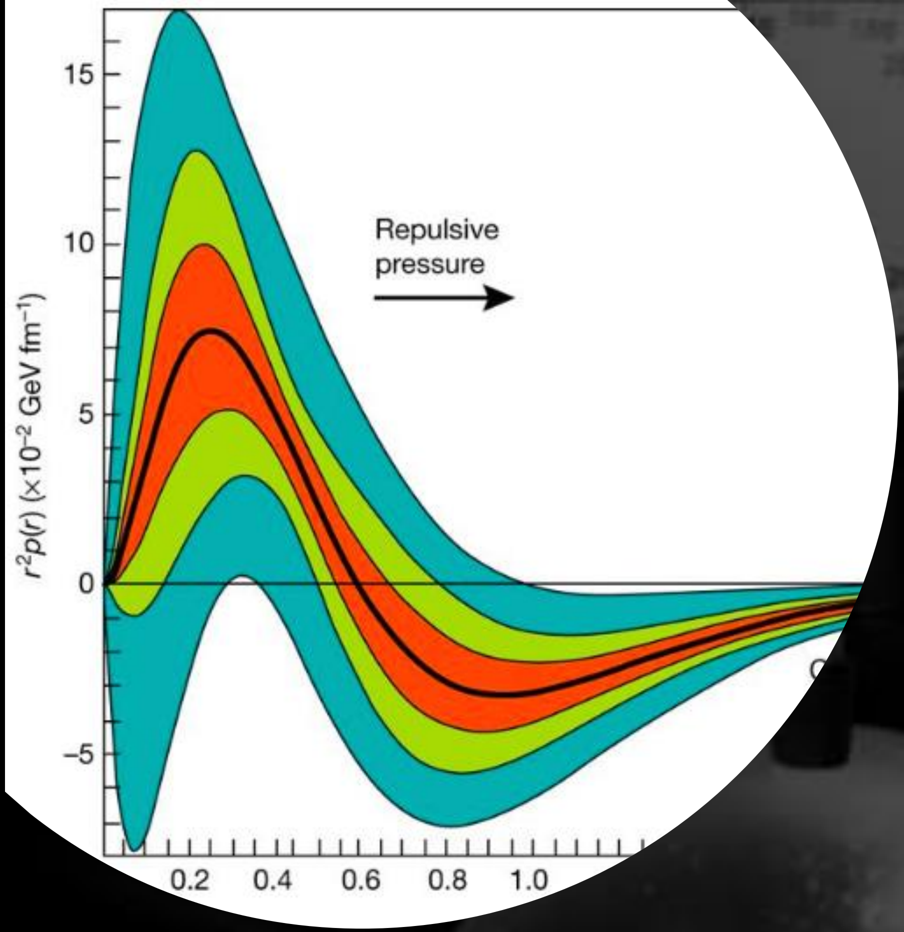


Nuclear femtography as a bridge from the nucleon to neutron stars

QCD with EIC
IIT Bombay
January 4-7, 2020

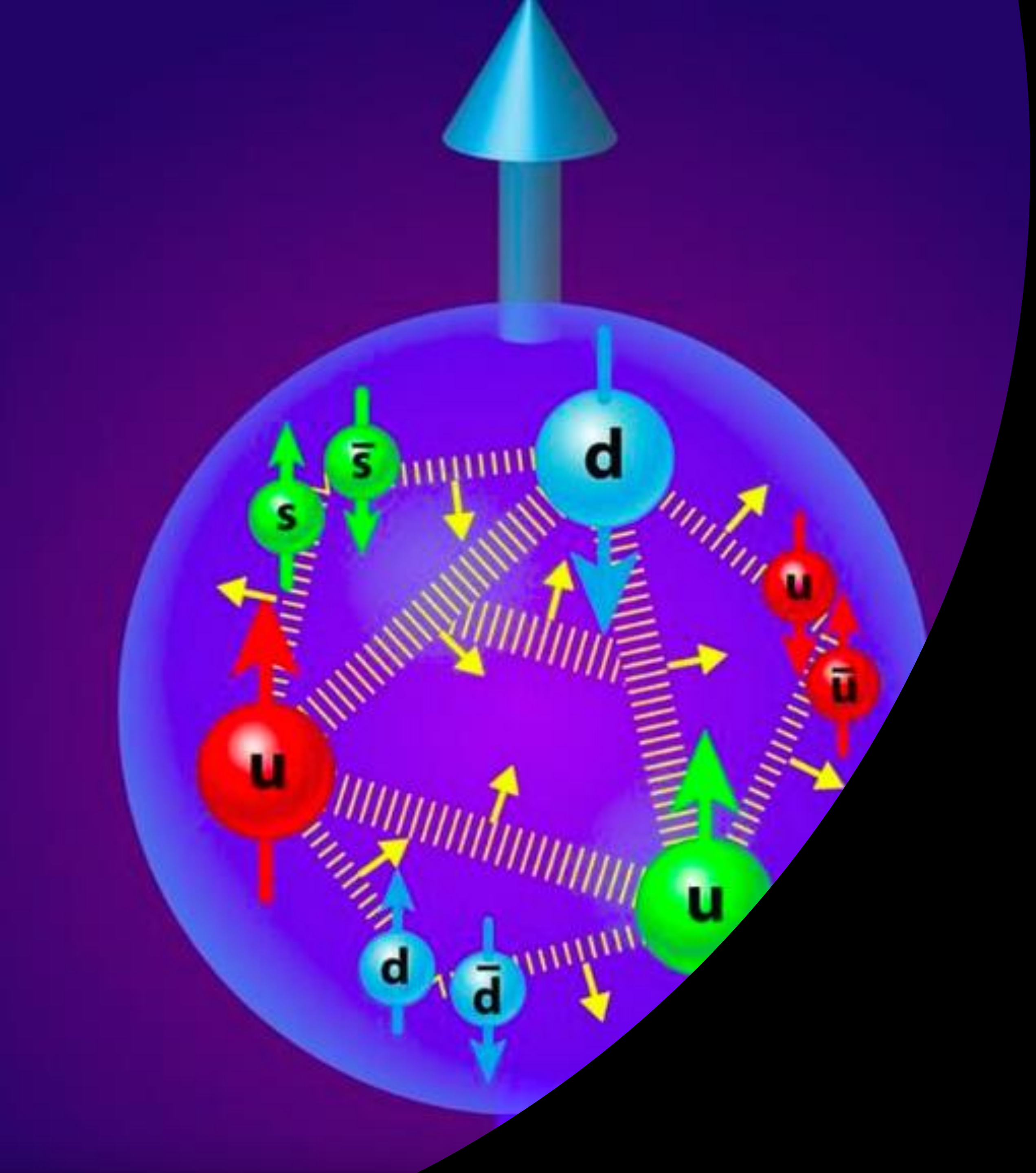
SIMONETTA LIUTI

UNIVERSITY OF VIRGINIA



Burkert, Elouadrhiri, Girod, Nature 557, 396 (2018)

- **“The average peak pressure near the center is about 10^{35} pascals, which exceeds the pressure estimated for the most densely packed known objects in the Universe, neutron stars”**



How is the pressure distribution extracted from data?

(How does the proton/neutron get its mass and spin?)

Based on

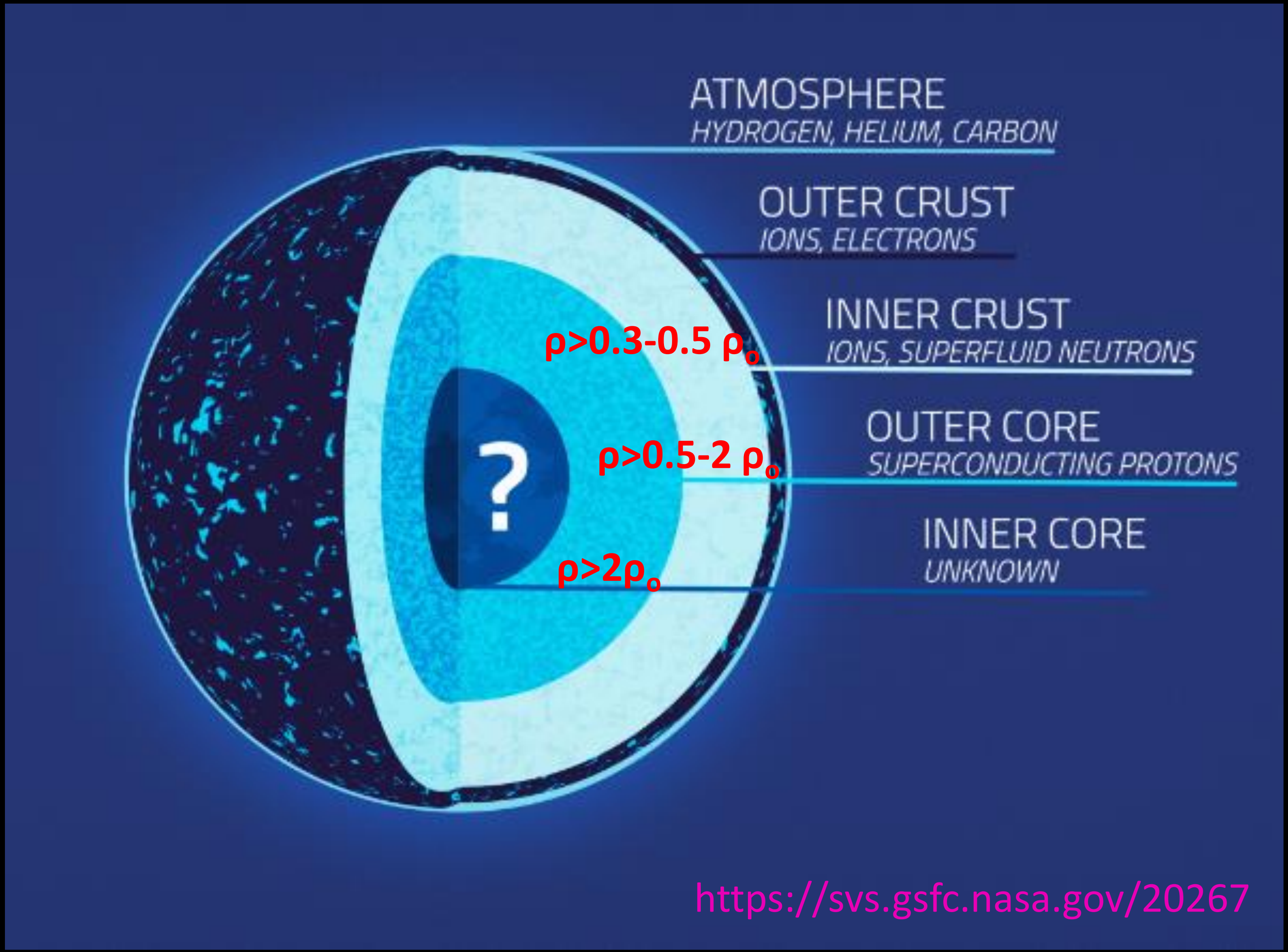
Bounds on the Equation of State of Neutron Stars from High Energy Deeply Virtual Exclusive Experiments

Abha Rajan,[1,*] Tyler Gorda,[2,†] Simonetta Liuti,[2,‡] and Kent Yagi[2,§]
[1] *Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA.*
[2] *Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.*

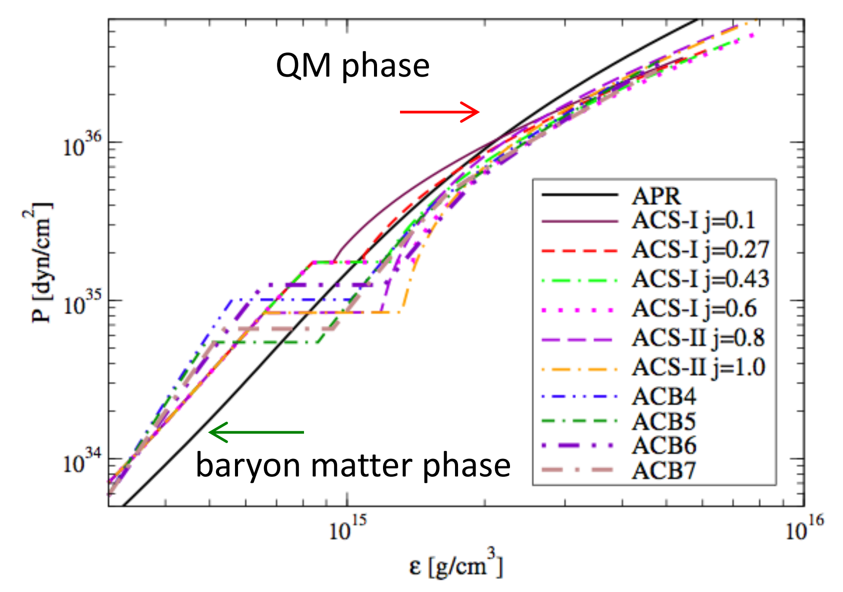
The recent detection of gravitational waves from merging neutron star events has opened a new window on the many unknown aspects of their internal dynamics. A key role in this context is played by the transition from baryon to quark matter described in the neutron star equation of state (EoS). In particular, the binary pulsar observation of heavy neutron stars requires appropriately stiff dense matter in order to counter gravitational collapse, at variance with the predictions of many phenomenological quark models. On the other side, the LIGO observations favor a softer EoS therefore providing a lower bound to the equation stiffness. We introduce a quantum chromodynamics (QCD) description of the neutron star's high baryon density regime where the pressure and energy density distributions are directly obtained from the matrix elements of the QCD energy momentum tensor. Recent ab initio calculations allow us to evaluate the energy-momentum tensor in a model independent way including both quark and gluon degrees of freedom. Our approach is a first effort to replace quark models and effective gluon interactions with a first principles, fully QCD-based description. Most importantly, the QCD energy momentum tensor matrix elements are connected to the Mellin moments of the generalized parton distributions which can be measured in deeply virtual exclusive scattering experiments. As a consequence, we establish a connection between observables from high energy experiments and from the analysis of gravitational wave events. Both can be used to mutually constrain the respective sets of data. In particular, the emerging QCD-based picture is consistent with the GW170817 neutron star merger event once we allow a first-order phase transition ...ow-density nuclear matter EoS to the newly-constructed high-density quark-gluon one.

arXiv:1812.01479

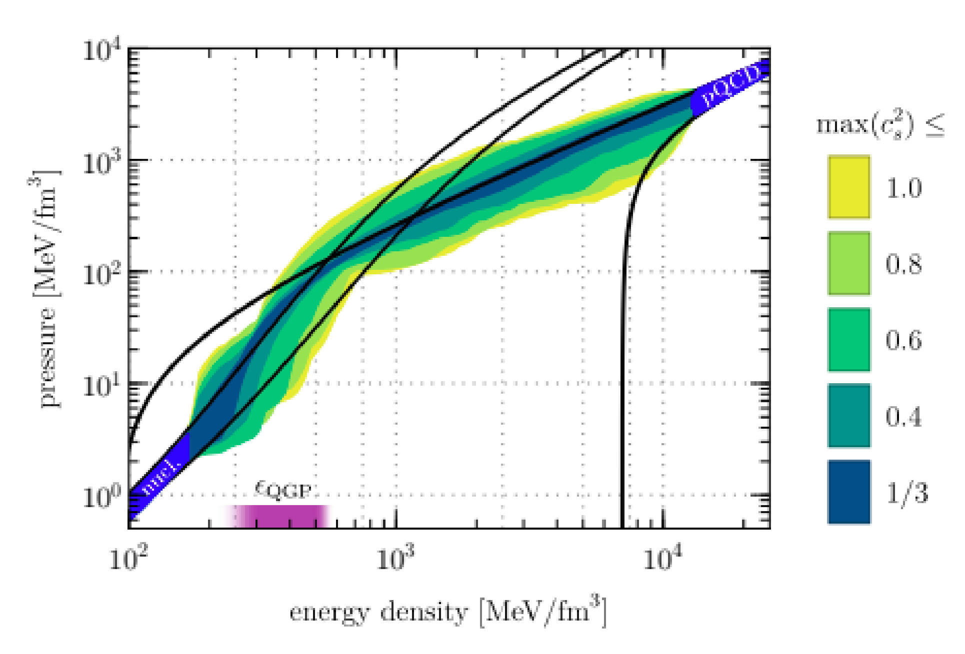
What governs the EoS of neutron stars?



Pascalidhis et al., arXiv:1712.00451

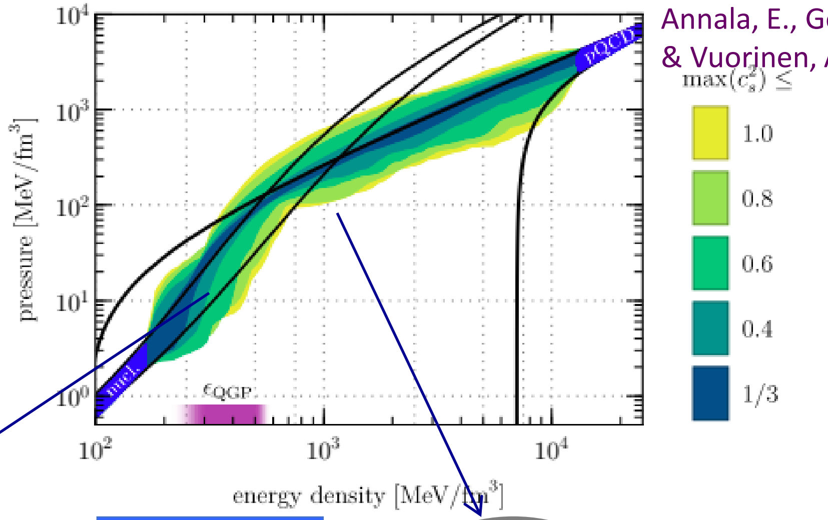


Annala, E., Gorda, T., Kurkela, A., Nattila, J., & Vuorinen, A. arXiv:1903.09121

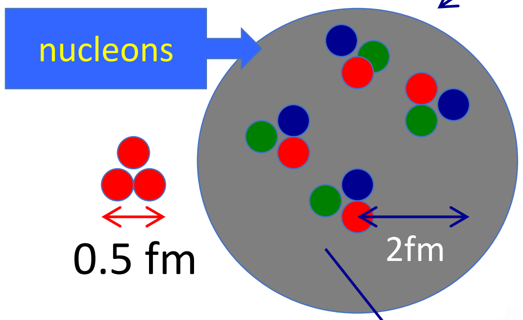


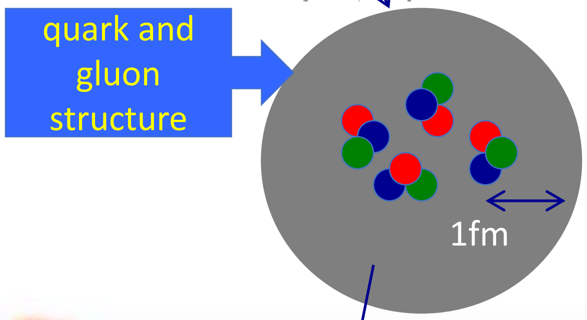
" …the existence of quark-matter cores inside very massive NSs should be considered the standard scenario, not an exotic alternative. QM is altogether absent in NS cores only under very specific conditions,…"

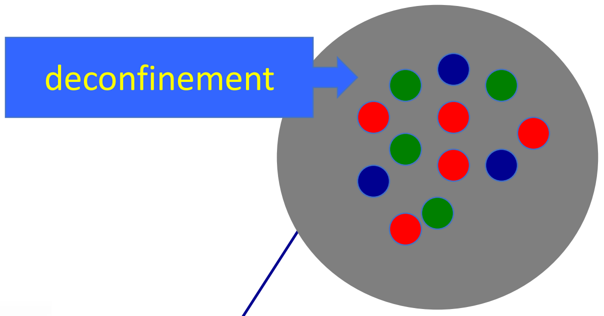
Densities and distance scales

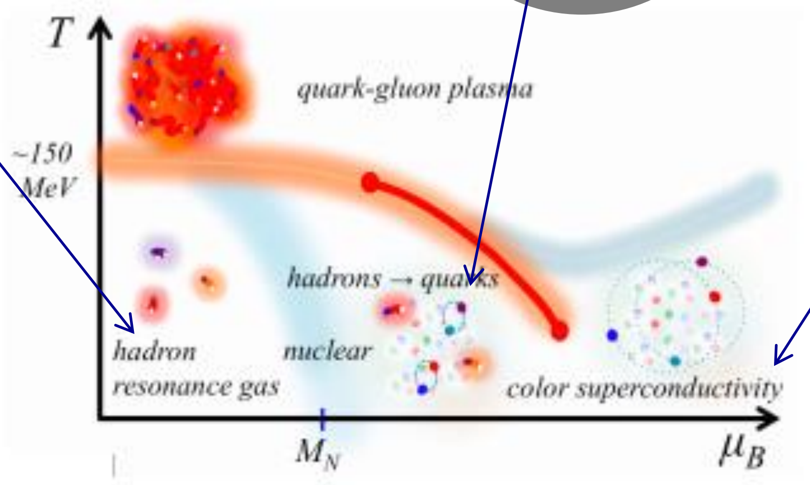


Annala, E., Gorda, T., Kurkela, A., Nattila, J., & Vuorinen, A. arXiv:1903.09121









G. Baym et al. arXiv:1707.04966

- In lieu of the nucleon bag model, the EoS in the quark matter phase can be inferred directly from the QCD Energy Momentum Tensor (EMT) matrix elements between nucleon states

- In lieu of the bag constant, B, spatial coordinates/distances play a fundamental role

Evaluating the mechanical properties of the proton

$$\mathcal{L}_{QCD} = \overline{\psi}\left(i\gamma_\mu D^\mu - m\right)\psi - \frac{1}{4}F_{a,\mu\nu}F_a^{\mu\nu}$$

Invariance of L_{QCD} under **translations** and **rotations**

Energy Momentum Tensor

from **translation** inv. ➡ $$T_{QCD}^{\mu\nu} = \frac{1}{4}\,\overline{\psi}\,\gamma^{(\mu}D^{\nu)}\psi + Tr\left\{F^{\mu\alpha}F_\alpha^\nu - \frac{1}{2}g^{\mu\nu}F^2\right\}$$

Angular Momentum Tensor

from **rotation** inv. ➡ $$M_{QCD}^{\mu\nu\lambda} = x^\nu T_{QCD}^{\mu\lambda} - x^\lambda T_{QCD}^{\mu\nu}$$

The QCD Energy Momentum Tensor

Mass

Momentum density

$$
\begin{bmatrix}
\frac{E^2+B^2}{2} & S_x & S_y & S_z \\
S_x & s_{xx} & s_{xy} & s_{xz} \\
S_y & s_{yx} & s_{yy} & s_{yz} \\
S_z & s_{zx} & s_{zy} & s_{zz}
\end{bmatrix}
$$

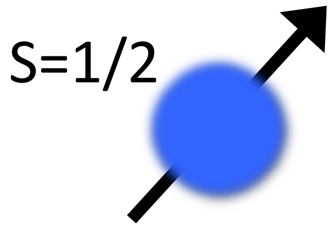
Momentum density

Shear stress

Pressure

$$
\boxed{T^{mn} = \frac{1}{4} iq\bar{y}\left(g^m \overleftrightarrow{D}^n + g^n \overleftrightarrow{D}^m\right)y + Tr\left\{F^{ma}F_a^n - \frac{1}{2}g^{mn}F^2\right\}} \longrightarrow \boxed{M^{mnl} = x^n T^{ml} - x^l T^{mn}}
$$

Angular Momentum density



QCD EMT matrix element between proton states

$$\langle p', \Lambda \mid T^{\mu\nu}_{\mathrm{q,g}} \mid p, \Lambda\rangle = A(t)\bar{U}(p',\Lambda')[\gamma^\mu P^\nu + \gamma^\nu P^\mu]U(p,\Lambda) + B(t)\bar{U}(p',\Lambda')i\,\frac{\sigma^{\mu(\nu}\Delta^{\nu)}}{2M}U(p,\Lambda)$$
$$+C(t)[\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu}]\bar{U}(p',\Lambda')U(p,\Lambda) + \widetilde{C}(t)g^{\mu\nu}\bar{U}(p',\Lambda')U(p,\Lambda)$$

forward

off-forward

q and g not separately conserved

$$\begin{cases} P = \dfrac{p+p'}{2} \\ D = p' - p = q - q' \\ t = (p - p')^2 = D^2 \end{cases}$$

Direct calculation of EMT form factors

Donoghue et al. PLB529 (2002),

A. Freese , QCD Evolution 2019

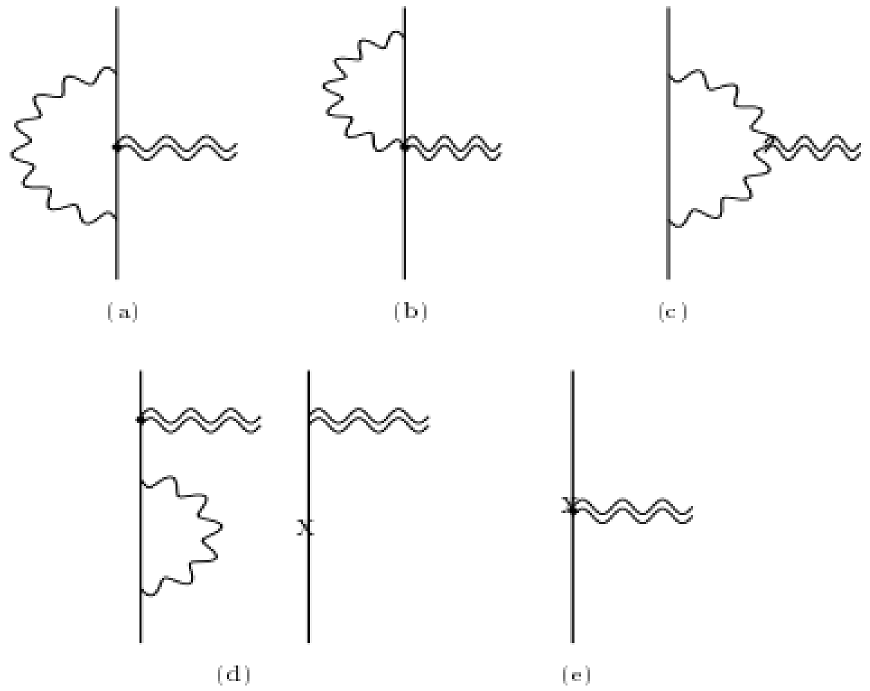
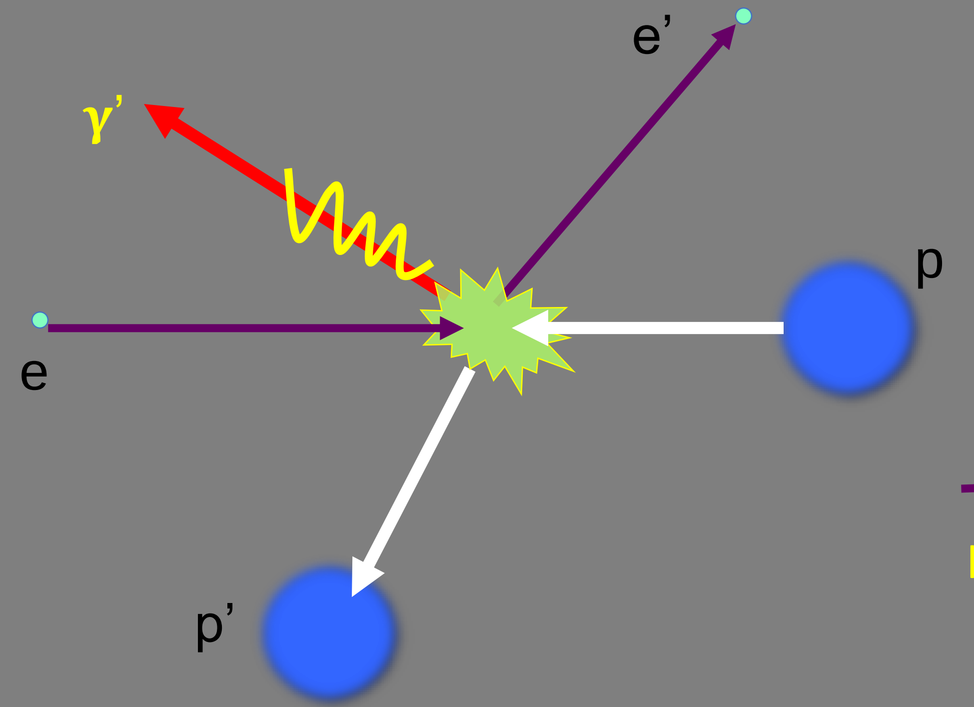
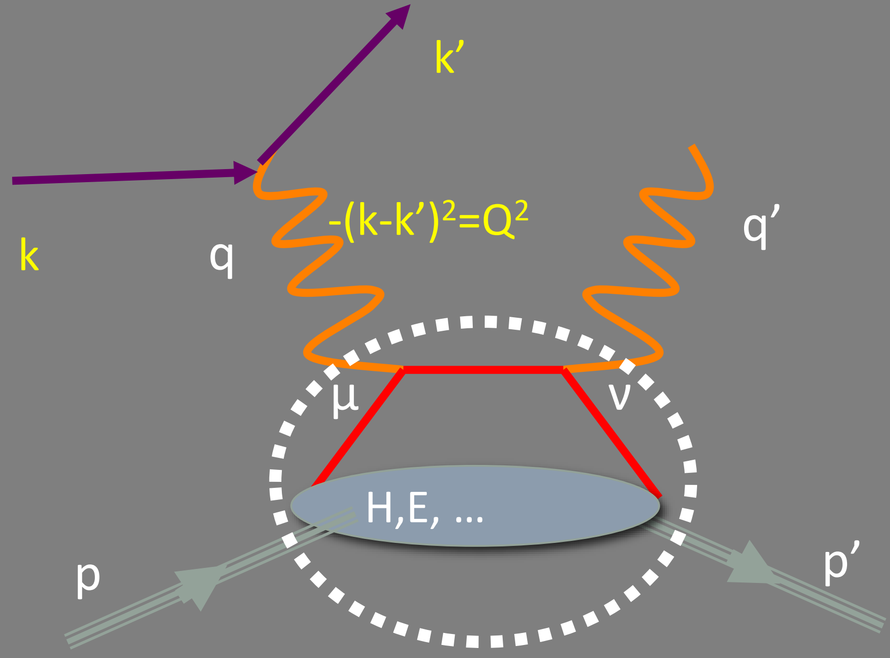


Figure 2: Feynman diagrams for spin 1/2 radiative corrections to $T_{\mu\nu}$.

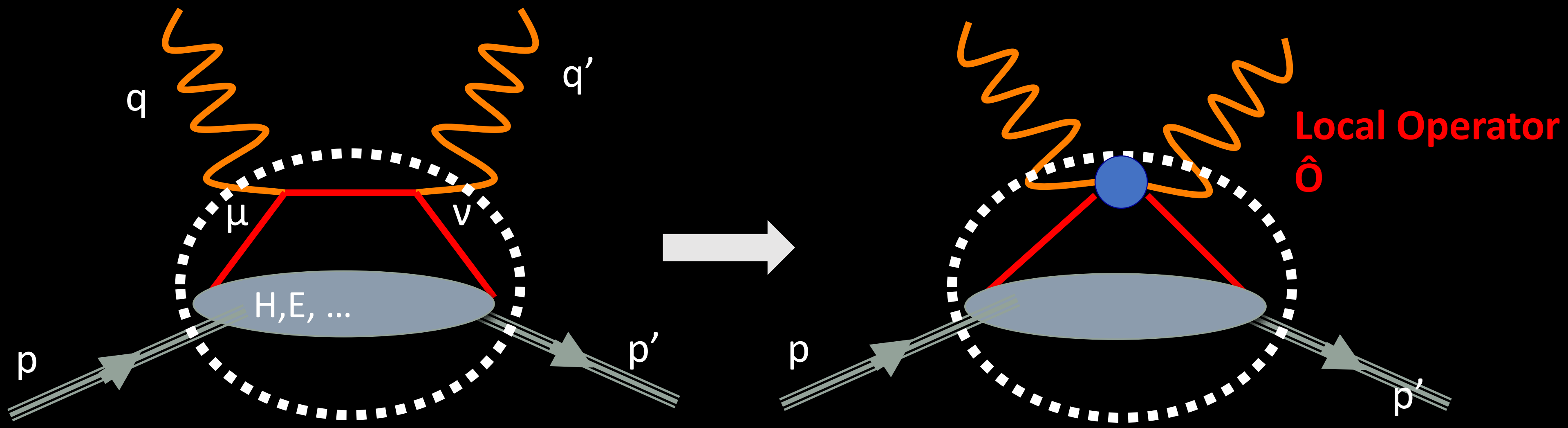
Deeply Virtual Compton Scattering (X. Ji, 1997)

$$ep \to e'g'p'$$





EMT matrix elements from Generalized Parton Distributions Moments



- Large momentum transfer $Q^2 >> M^2$ ➔ "deep"
- Large Invariant Mass $W^2 >> M^2$ ➔ equivalent to an "inelastic" process

2nd Mellin moments

From OPE ⟺ From EMT

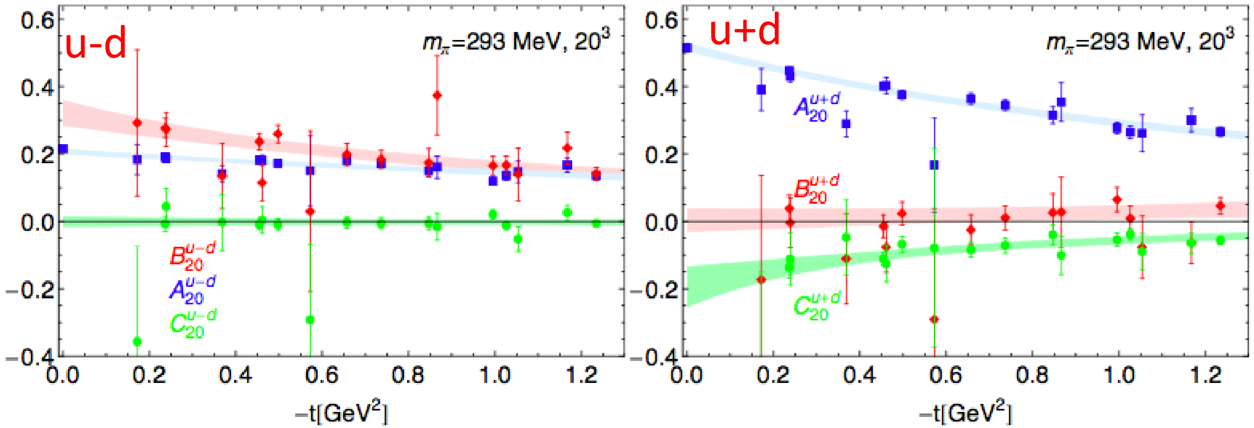
$$\int dx\, x H(x,\xi,t) = \boxed{A_{20}(t) + \xi^2 C_{20}(t)} \equiv \boxed{A(t) + \xi^2 C(t)}$$

$$\int dx\, x E(x,\xi,t) = \boxed{B_{20}(t) - \xi^2 C_{20}(t)} \equiv \boxed{B(t) - \xi^2 C(t)}$$

D-term

Physical interpretation of EMT form factors

$\frac{1}{2}(A_q + B_q) = J_q = \frac{1}{2}(A_{20} + B_{20})$	$J_q^i = \int d^3r \epsilon^{ijk} r_j T_{0k}$ Angular Momentum
$A_q = \langle x_q \rangle = A_{20}$	Momentum
$C_q = \text{Internal Forces} = C_{20}$	$\int d^3r \left(r^i r^j - \delta^{ij} r^2\right) T_{ij}$ Pressure



Ph. Haegler, JoP: **295** (2011) 012009

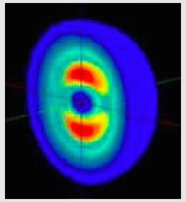
Static Approximation

Landau&Lifshitz, Vol.7

M. Polyakov, hep-ph/0210165

M. Polyakov, P. Schweitzer, arXiv:1805.06596

Deuteron

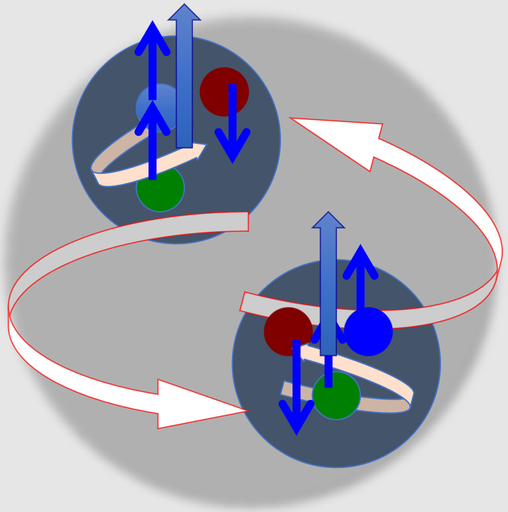


Angular momentum sum rule for spin one hadronic systems

Swadhin K. Taneja,[1,*] Kunal Kathuria,[2,†] Simonetta Liuti,[2,‡] and Gary R. C[illegible]tein[3,§]

PRD86(2012)

7 conserved form factors!



$$
\begin{aligned}
\langle p', \Lambda' | T^{\mu\nu} | p, \Lambda \rangle = & -\frac{1}{2} P^\mu P^\nu (\epsilon'^* \epsilon) \mathcal{G}_1(t) - \frac{1}{4} P^\mu P^\nu \frac{(\epsilon P)(\epsilon'^* P)}{M^2} \mathcal{G}_2(t) \\
& -\frac{1}{2} \left[\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2 \right] (\epsilon'^* \epsilon) \mathcal{G}_3(t) - \frac{1}{4} \left[\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2 \right] \frac{(\epsilon P)(\epsilon'^* P)}{M^2} \mathcal{G}_4(t) \\
& + \frac{1}{4} \left[\left(\epsilon'^{*\mu} (\epsilon P) + \epsilon^\mu (\epsilon'^* P) \right) P^\nu + \mu \leftrightarrow \nu \right] \mathcal{G}_5(t) \\
& + \frac{1}{4} \left[\left(\epsilon'^{*\mu} (\epsilon P) - \epsilon^\mu (\epsilon'^* P) \right) \Delta^\nu + \mu \leftrightarrow \nu + 2 g_{\mu\nu} (\epsilon P)(\epsilon'^* P) - (\epsilon'^{*\mu} \epsilon^\nu + \epsilon'^{*\nu} \epsilon^\mu) \Delta^2 \right] \mathcal{G}_6(t) \\
& + \frac{1}{2} \left[\epsilon^{*\prime\mu} \epsilon^\nu + \epsilon'^{*\nu} \epsilon^\mu \right] \mathcal{G}_7(t) + g^{\mu\nu} (\epsilon'^* \epsilon) M^2 \mathcal{G}_8(t)
\end{aligned}
$$

General rule to count form factors: t-channel J^{PC} q. numbers

Haegler, PLB(2004)
Z.Chen&Ji, PRD(2005)

n	$J^{PC}(S;L)$				
0	0^{+-}	$1^{--}(1;0,2)$			
1	$0^{++}(1;1)$	1^{-+}	$2^{++}(1;1,3)$		
2	0^{+-}	$1^{--}(1;0,2)$	2^{+-}	$3^{--}(1;2,4)$	
3	$0^{++}(1;1)$	1^{-+}	$2^{++}(1;1,3)$	3^{-+}	$4^{++}(1;3,5)$
...	...				

TABLE III: J^{PC} of the vector operators with $(S;L,L')$ for the corresponding $N\bar{N}$ state. Where there are no $(S;L,L')$ values there are no matching quantum numbers for the $N\bar{N}$ system.

Nucleon

	$L=0$	1	2	3	4	...
$S=0$	J^{PC} 0^{-+}	1^{+-}	2^{-+}	3^{+-}	4^{-+}	
$S=1$	1^{--}	0^{++}	1^{--}	2^{++}	3^{--}	
		1^{++}	2^{--}	3^{++}	4^{--}	
		2^{++}	3^{--}	4^{++}	5^{--}	

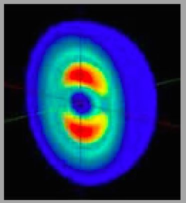
TABLE I: J^{PC} of the $N\bar{N}$ states.

Deuteron

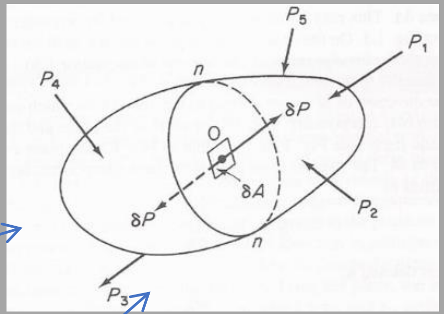
	$L=0$	1	2	3	4	...
$S=0$	J^{PC} 0^{++}	1^{--}	2^{++}	3^{--}	4^{++}	
$S=1$	1^{+-}	0^{-+}	1^{+-}	2^{-+}	3^{+-}	
		1^{-+}	2^{+-}	3^{-+}	4^{+-}	
		2^{-+}	3^{+-}	4^{-+}	5^{+-}	
$S=2$	2^{++}	1^{--}	0^{++}	1^{--}	2^{++}	
		2^{--}	1^{++}	2^{--}	3^{++}	
		3^{--}	2^{++}	3^{--}	4^{++}	
			3^{++}	4^{--}	5^{++}	
			4^{++}	5^{--}	6^{++}	

TABLE II: J^{PC} of the $d\bar{d}$ states.

S.L., Talk at INT U. Washington, 2012



S.Taneja et al., PRD86(2012)



From OPE ⟺ From EMT

$$2\int dx x[H_1(x,\xi,t) - \frac{1}{3}H_5(x,\xi,t)] = \mathcal{G}_1(t) + \boxed{\xi^2\mathcal{G}_3(t)}$$

Momentum

$$2\int dx x H_2(x,\xi,t) = \mathcal{G}_5(t)$$

Angular Momentum

Double flip
D-term dependent
on polarization

$$2\int dx x H_3(x,\xi,t) = \mathcal{G}_2(t) + \boxed{\xi^2\mathcal{G}_4(t)}$$

Quadrupole

$$-4\int dx x H_4(x,\xi,t) = \xi\mathcal{G}_6(t)$$

ξ-odd

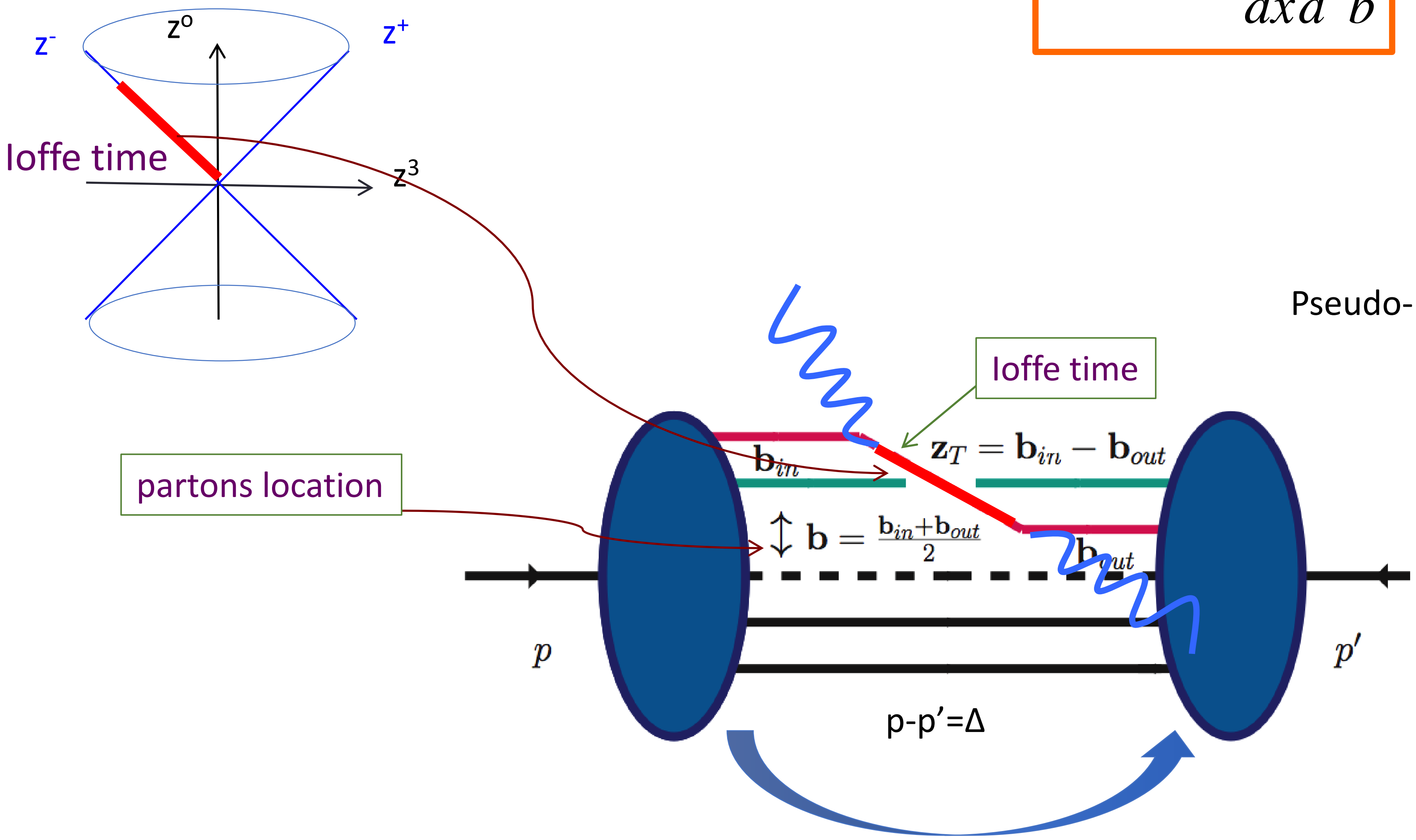
$$\int dx x H_5(x,\xi,t) = -\frac{t}{8M_D^2}\mathcal{G}_6(t) + \frac{1}{2}\mathcal{G}_7(t)$$

Connected to b_1 SR

Connecting with observables: work in progress with Brandon Kriesten, Abha Rajan Swadhin Taneja

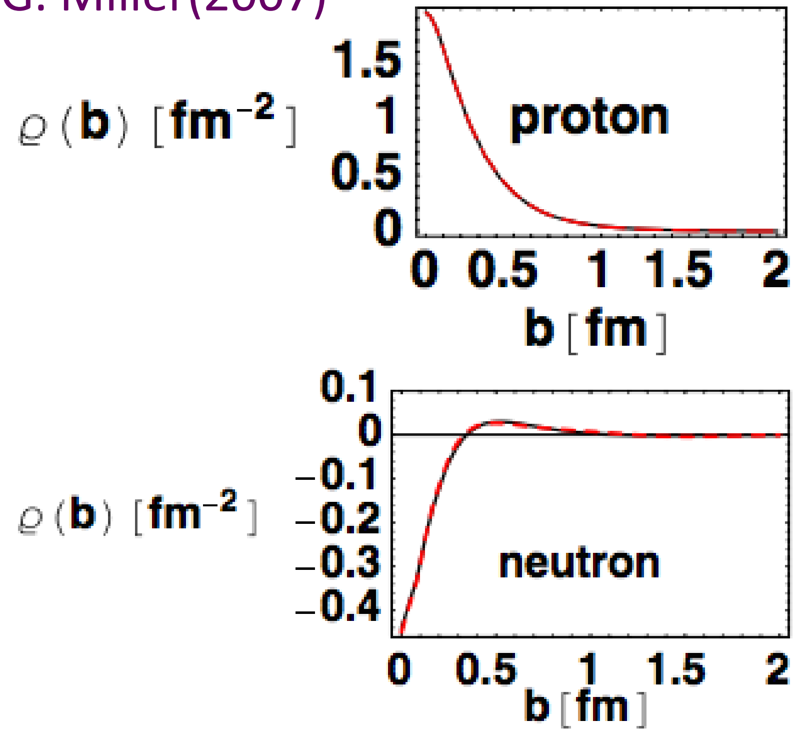
Two distinct distance scales

$$q(x,\vec{b}) = \frac{dn}{dx\,d^2\vec{b}}$$

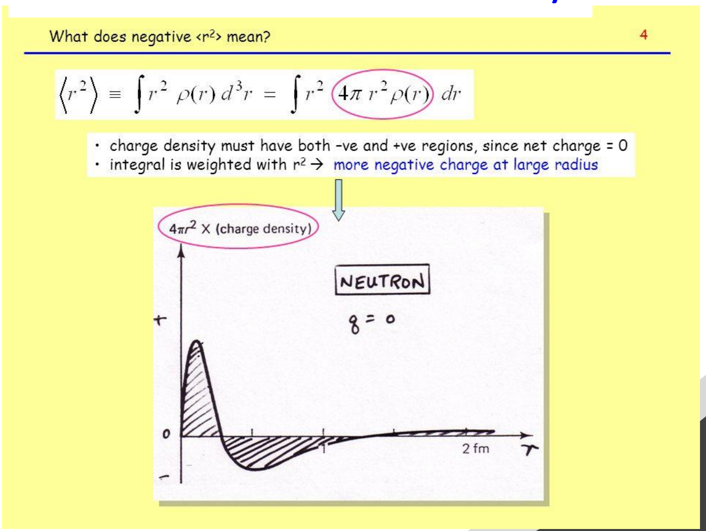


Pseudo-pdfs!

G. Miller(2007)



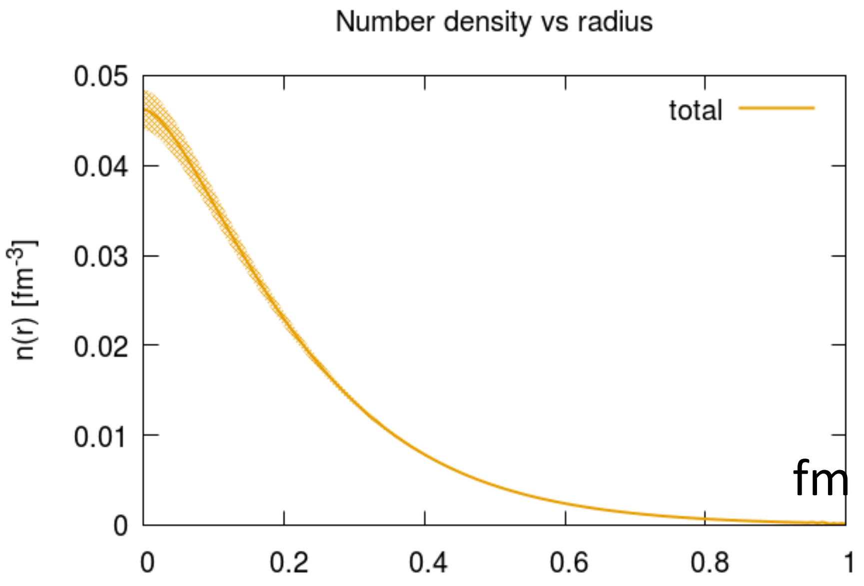
Neutron “textbook” density

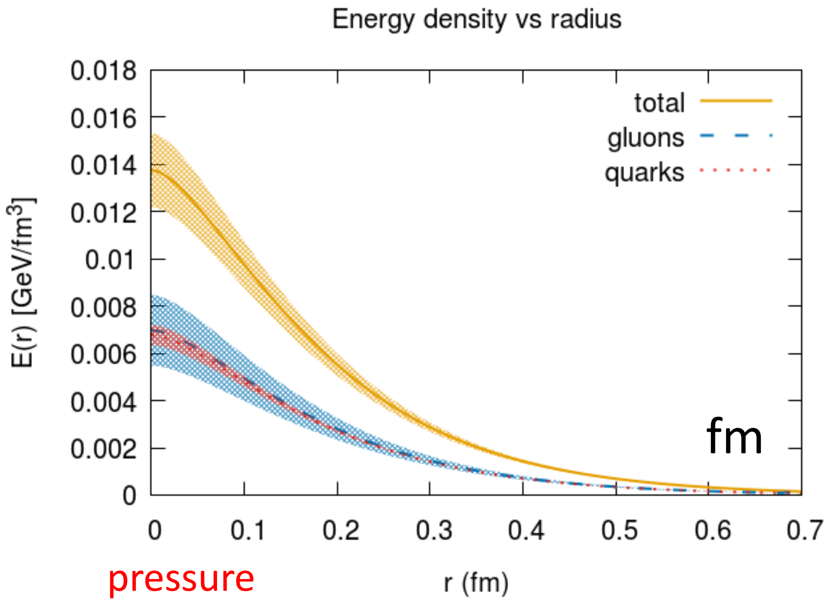


Using $\boxed{q(x,\vec{b}) = \frac{dn}{dx\, d^2\vec{b}}}$ we can

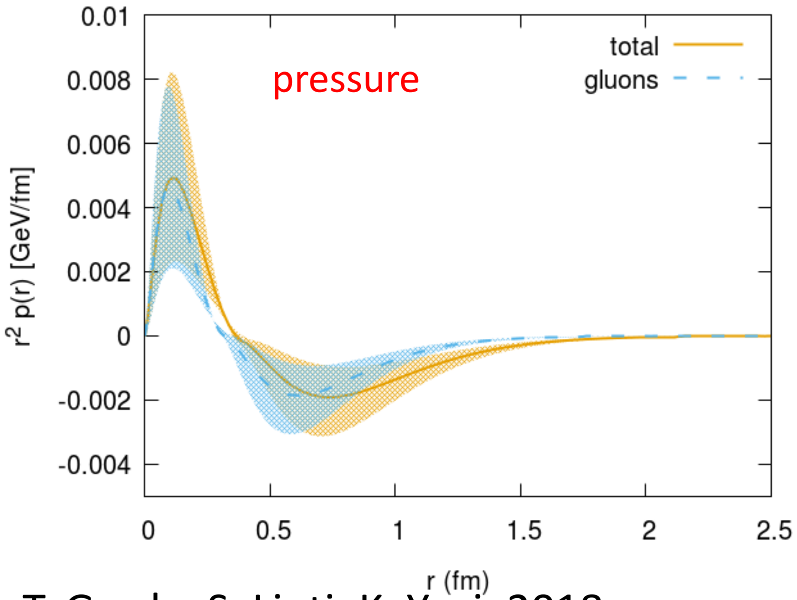
map out faithfully the spatial quark distributions in the transverse plane
(no modeling/approximation)

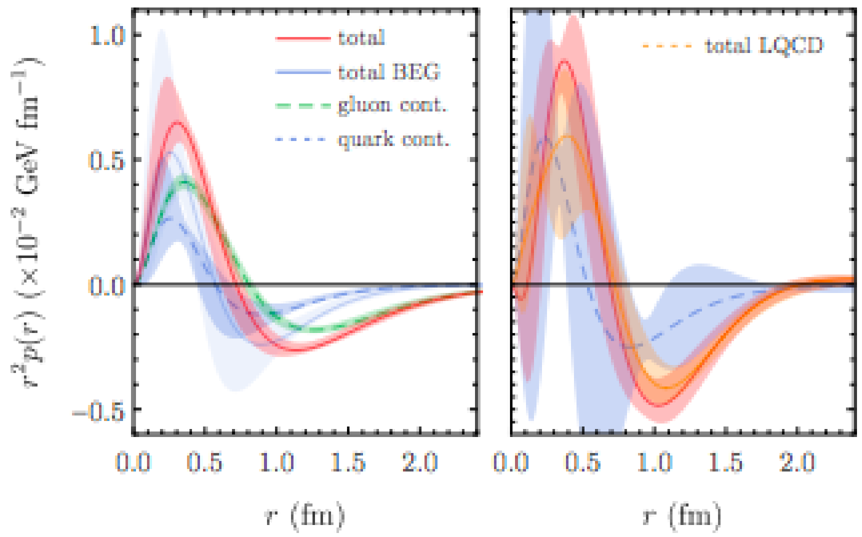
Soper (1977), Burkardt (2001)





pressure

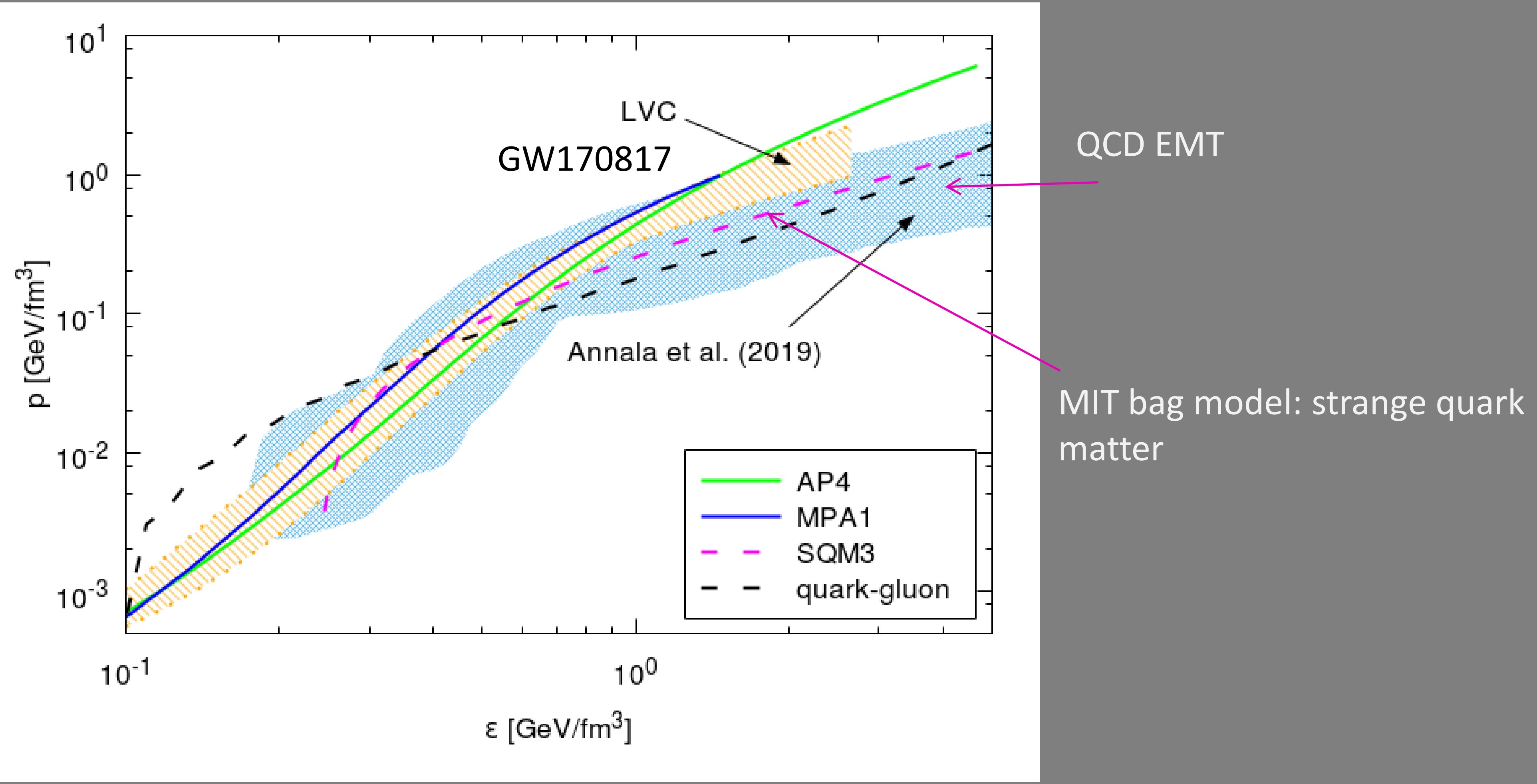


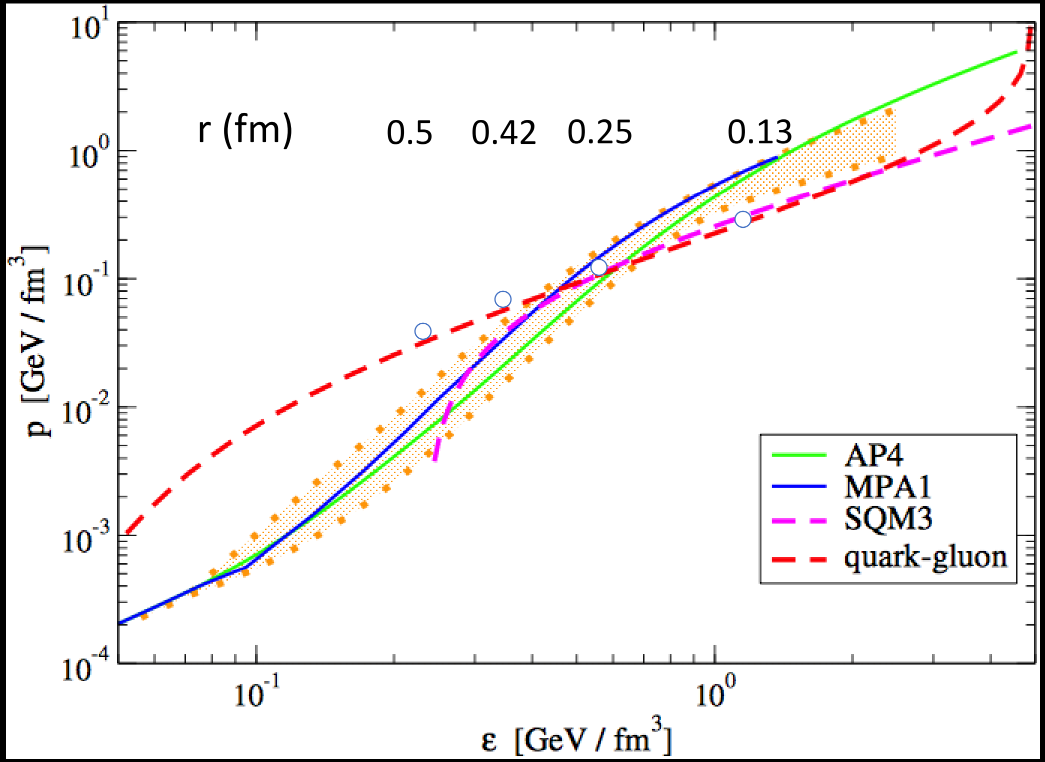


A. Rajan, T. Gorda, S. Liuti, K. Yagi, 2018

Detmold, Shahanan, Phys.Rev.Lett. 122 (2019)

Rajan, Gorda, SL, Yagi, arXiv:1812.01479



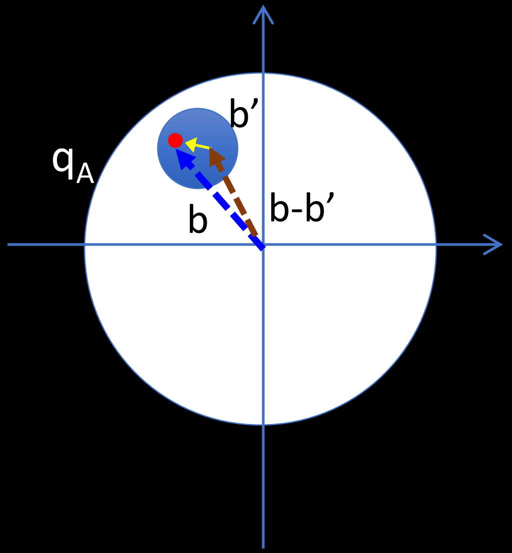


E (GeV/fm^3)	r (fm)
0.2	0.48
0.3	0.426
0.6	0.325
1	0.25
2	0.134
3	0.05

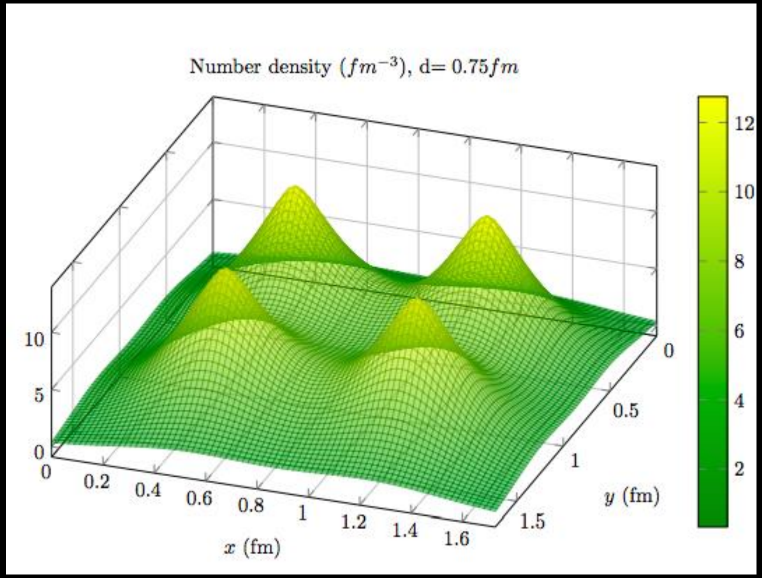
$$q_A(b) = \int d^2b' \rho_A(|\vec{b} - \vec{b}'|) q_N(b')$$

$$\approx k_F^3 \int d^2\beta \, q_N(|\vec{b} - \vec{\beta}|), \qquad \vec{\beta} = \vec{b} - \vec{b}'$$

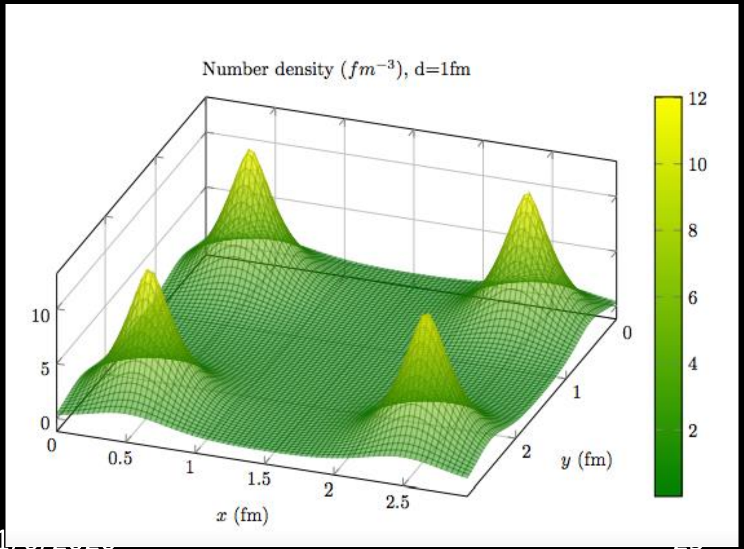
Nuclear Spatial Density



⟨**β**⟩= 0.75 fm

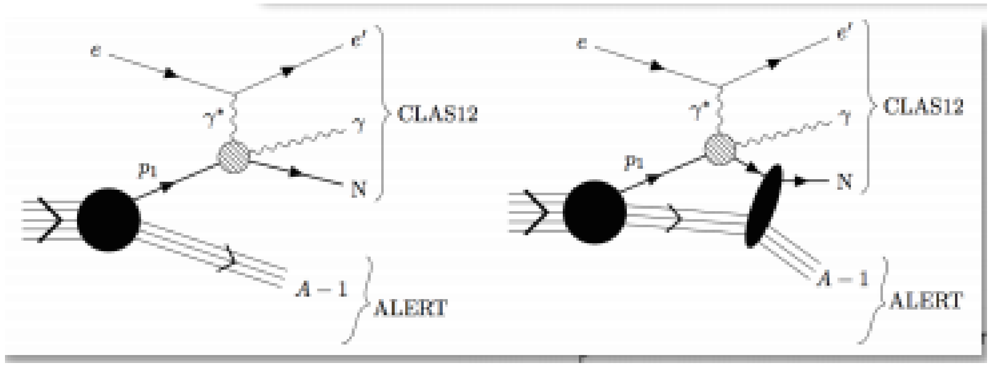


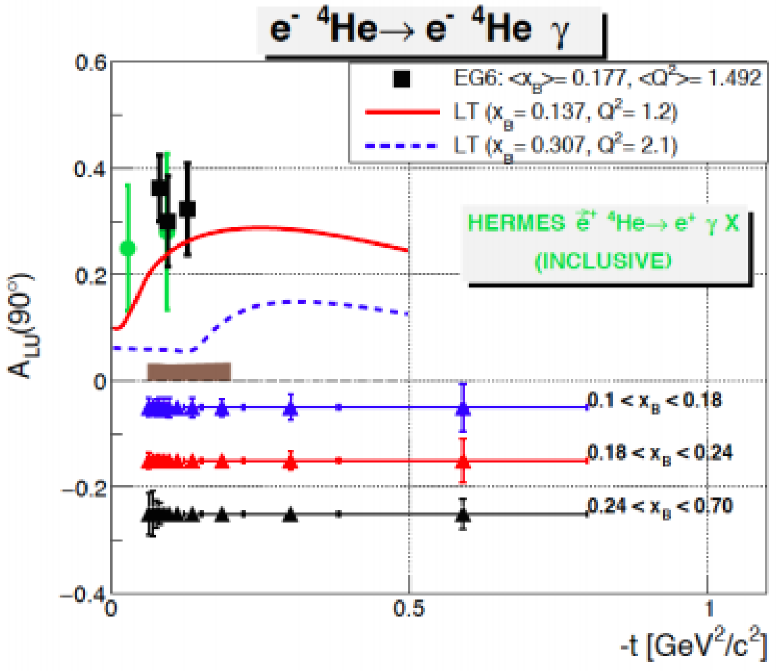
⟨**β**⟩= 2 fm



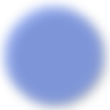
ALERT Proposal at Jefferson Lab: Nuclear Exclusive and Semi-inclusive Measurements with A New CLAS12 Low Energy Recoil Tracker

W. Armstrong. M. Hattawy et al.



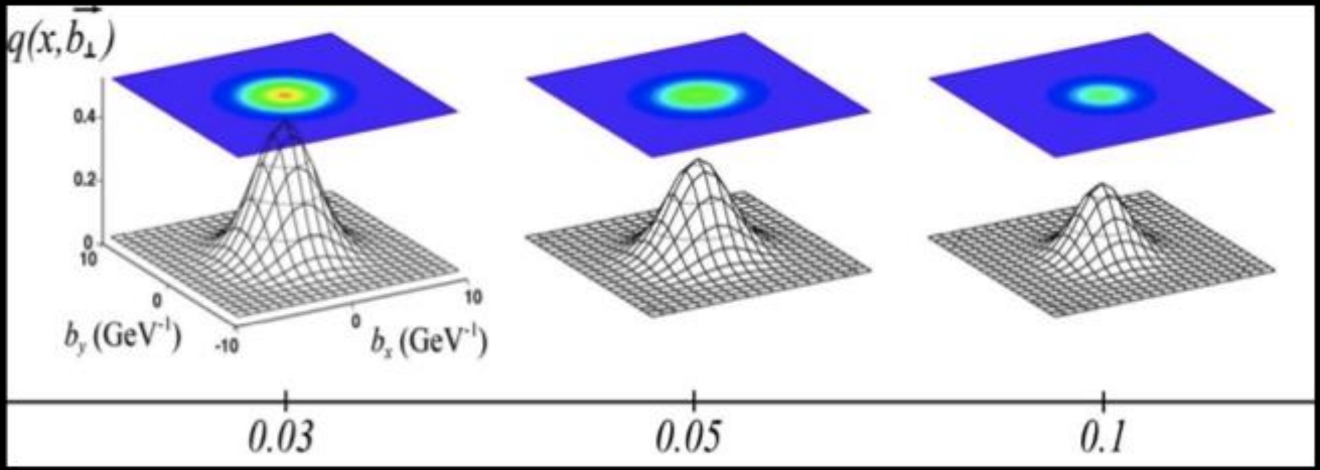


S=0



$$\langle p' \mid T^{\mu\nu} \mid p\rangle = 2\left[A(t)P^\mu P^\nu + C(t)(\Delta^2 g^{\mu\nu} - \Delta^\mu\Delta^\nu)\right] + \tilde{C}(t) g^{\mu\nu}$$

Measuring the Nucleon Gravitomagnetic Form Factors



courtesy M. Defurne

Introducing the complete formalism

arXiv:1903.05742

Extraction of Generalized Parton Distribution Observables from Deeply Virtual Electron Proton Scattering Experiments

Brandon Kriesten,* Simonetta Liuti,† Liliet Calero Diaz,‡ Dustin Keller,§ and Andrew Meyer¶
Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.

Gary R. Goldstein**
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J. Osvaldo Gonzalez-Hernandez††
INFN, Torino

(Dated: April 6, 2019)

We provide the general expression of the cross section for exclusive deeply virtual photon electroproduction from a spin 1/2 target using current parameterizations of the off-forward correlation function in a nucleon for different beam and target polarization configurations up to twist three accuracy. All contributions to the cross section including deeply virtual Compton scattering, the Bethe-Heitler process, and their interference, are described within a helicity amplitude based framework which is also relativistically covariant and readily applicable to both the laboratory frame and in a collider kinematic setting. Our formalism renders a clear physical interpretation of the various components of the cross section by making a connection with the known characteristic structure of the electron scattering coincidence reactions. In particular, we focus on the total angular momentum, J_z, and on the orbital angular momentum, L_z. On one side, we uncover an avenue to a precise extraction of J_z, given by the combination of generalized parton distributions, $H+E$, through a generalization of the Rosenbluth separation method used in elastic electron proton scattering. On the other, we single out for the first time, the twist three angular modulations of the cross section that are sensitive to L_z. The proposed generalized Rosenbluth technique adds constraints and can

Phys. Rev. D (2020)

- ✓ **Supersedes previous work by Belitsky Kirchner Mueller and Kumericki Mueller**

- ✓ **The main advantage are :**

    - ✓ **Covariance (not just Lab frame): a desirable feature for the EIC**
    - ✓ **Transparent description of observables that ties into the TMD and other coincidence experiments picture**

A multi-step, multi-prong process: compare to imaging of blackhole

Event Horizon Telescope (EHT)

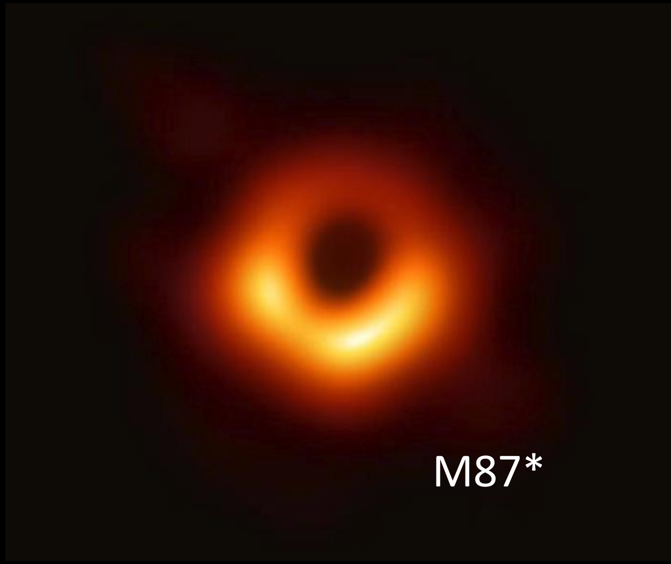
- ✓ Main idea: Very Long Baseline Interferometry (VLBI), an array of smaller telescopes synchronized to focus on the same object and act as a giant telescope
- ✓ Precision: large aperture (many telescopes widely spaced) and high frequency radio waves
- ✓ Data Management: 5 petabytes physically transported to a central location. Data from all eight sites were combined to create a composite set of images, revealing for the first time M87*'s event horizon.

It took nearly two decades to achieve !

Electron Ion Collider (EIC)

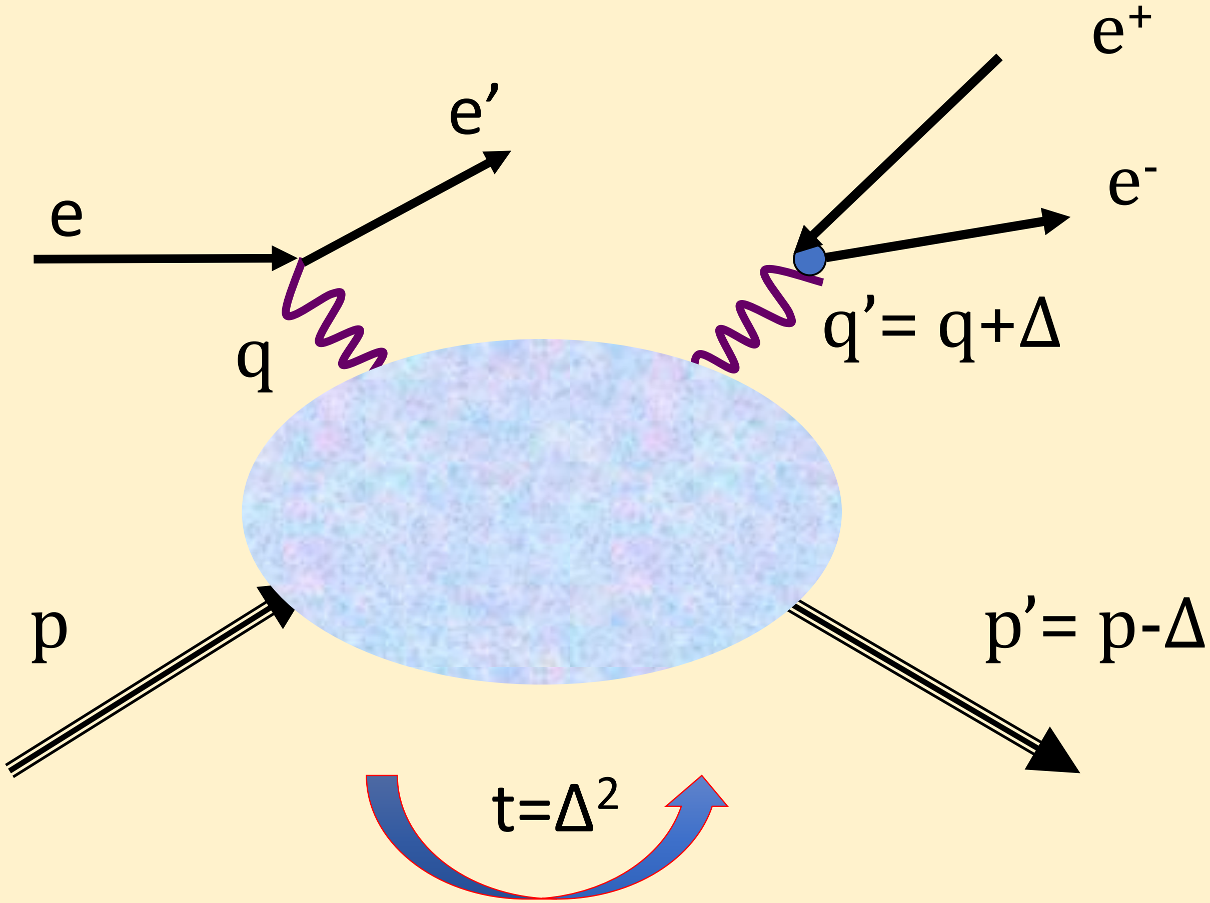
- ✓ Main idea: use DVCS, TCS, DVMP… and related processes as probes
- ✓ Precision: high luminosity in a wide kinematic range is key!
- ✓ Data Management: unprecedented amount of data need new AI based techniques to handle the image making

Date of first proton image?...



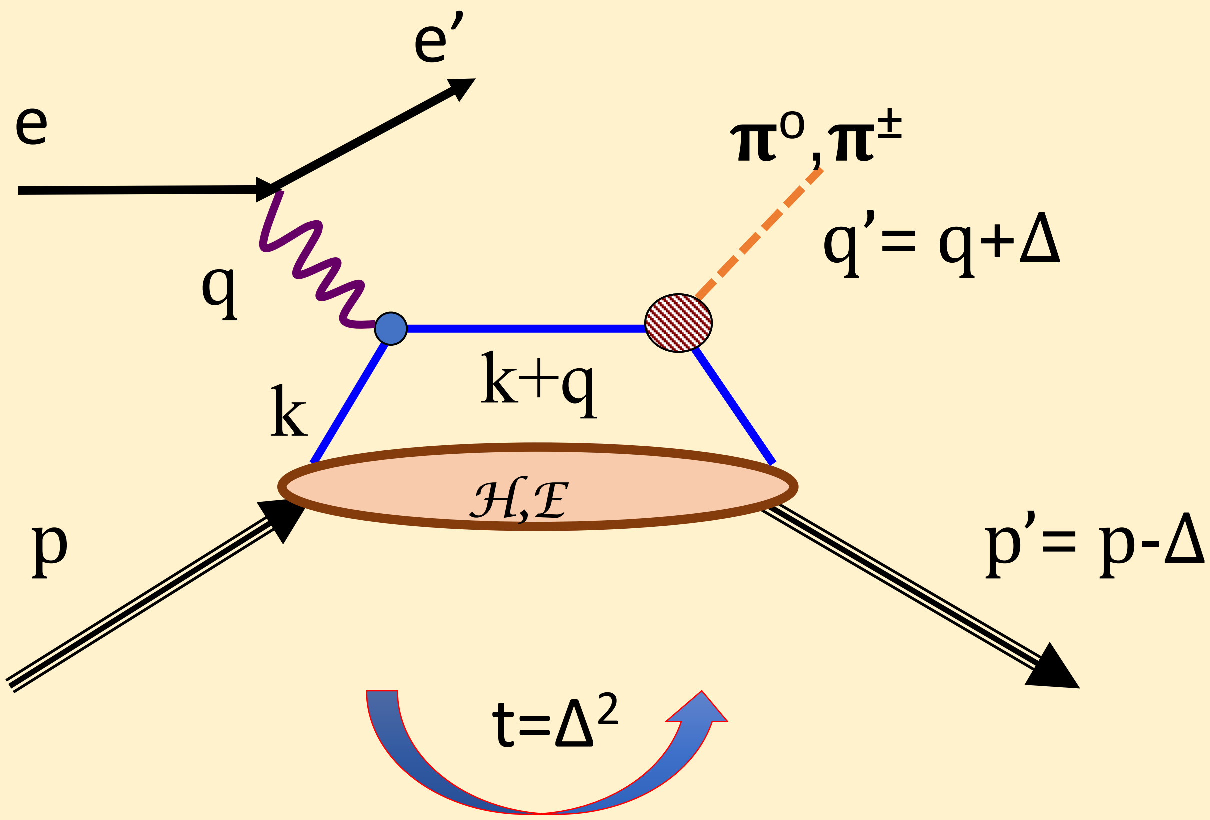
A multi-step, multi-prong process

- Deeply Virtual Compton Scattering
- Timelike Compton Scattering



A multi-step, multi-prong process

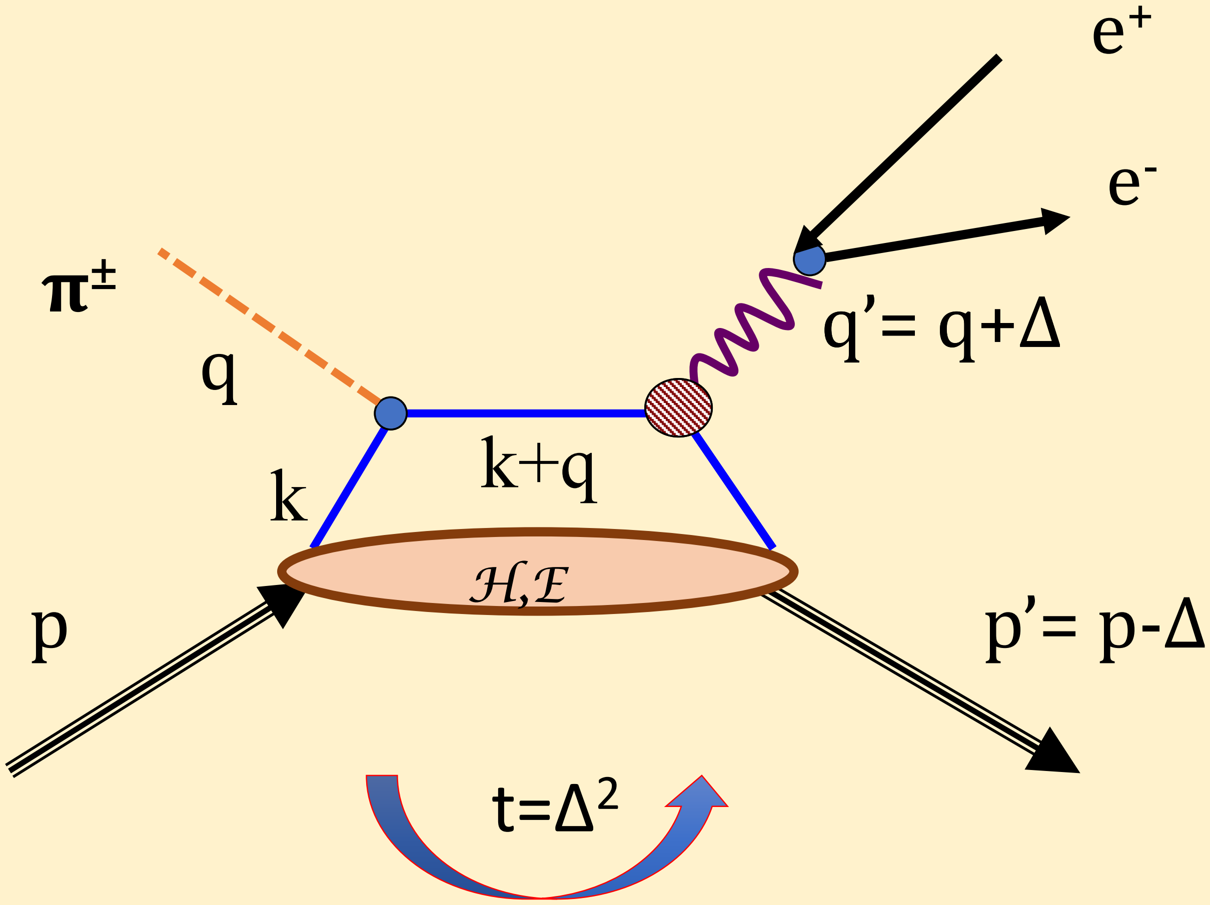
- Deeply Virtual Meson Production
- Exclusive Drell Yan

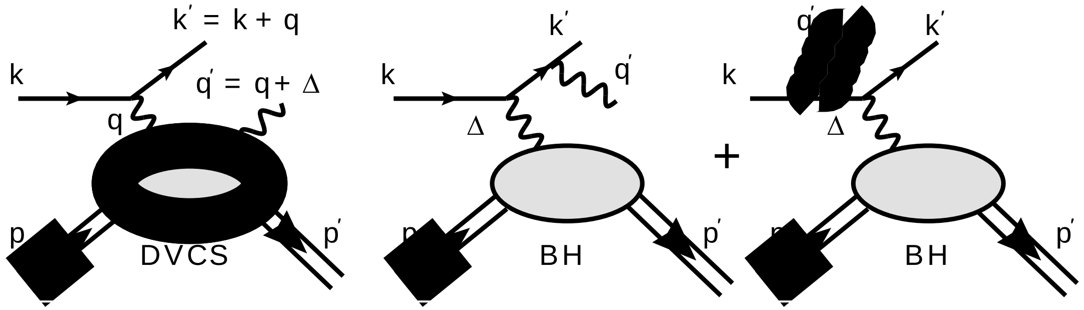


A multi-step, multi-prong process

Deeply Virtual Meson Production

Exclusive Drell Yan





$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}|T|^2 ,$$

$$T(k,p,k',q',p') = T_{DVCS}(k,p,k',q',p') + T_{BH}(k,p,k',q',p'),$$

DVCS

$$\frac{d^5\sigma_{DVCS}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}|T_{DVCS}|^2$$

twist two GPDs

twist three GPDs

$$= \frac{\Gamma}{Q^2(1-\epsilon)}\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi}$$

$$+ \sqrt{\epsilon(\epsilon+1)}\left[\cos\phi F_{UU}^{\cos\phi} + \sin\phi \cancel{F_{UU}^{\sin\phi}}\right]$$

$$+ \lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin\phi F_{LU}^{\sin\phi}$$

$$+ S_L\left[\cancel{F_{UL}} + \sqrt{\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi}\right]$$

$$+ \lambda_e \sqrt{1-\epsilon^2} F_{LL} + 2\lambda_e\sqrt{\epsilon(1-\epsilon)}\cos\phi F_{LL}^{\cos\phi}$$

$$+ |S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)$$

$$\epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\right)\Big]$$

$$+ \lambda_e S_L\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Observables

GPD	Twist	P_qP_p	TMD	$P_{Beam}P_p$ (DVCS)	$P_{Beam}P_p$ ($\mathcal{I}$)	
$\mathbf{H} + \frac{\xi^2}{1-\xi}E$	2	UU	f_1	$UU,\ LL,\ UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UU^{\cos\phi},\ LU^{\sin\phi}$	
$\widetilde{\mathbf{H}} + \frac{\xi^2}{1-\xi}\widetilde{E}$	2	LL	g_1	$UU,\ LL,\ UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\sin\phi},\ UT^{\frac{\cos\phi}{\sin\phi}},\ LT^{\cos\phi}$	
$\mathbf{E}$	2	UT	$f_{1T}^{\perp(*)}$	$UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UU^{\cos\phi},\ LU^{\sin\phi},\ UT,\ LT,\ UT^{\cos\phi},\ UT^{\sin\phi}$	
$\widetilde{\mathbf{E}}$	2	LT	g_{1T}	$UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UL^{\sin\phi},\ LL^{\cos\phi},\ UT^{\cos\phi},\ UT^{\sin\phi}$	
H+E	2	-	-	-	$UU^{\cos\phi},\ LU^{\sin\phi},\ UL^{\sin\phi},\ LL^{\cos\phi},\ UT^{\cos\phi},\ UT^{\sin\phi}$	
$2\widetilde{\mathbf{H}}_{\mathbf{2T}} + \mathbf{E}_{\mathbf{2T}} - \xi\widetilde{E}_{2T}$	3	UU	$f^\perp$	$UU^{\cos\phi},\ LU^{\sin\phi}$	UU, LU	
$2\widetilde{\mathbf{H}}'_{\mathbf{2T}} + \mathbf{E}'_{\mathbf{2T}} - \xi\widetilde{E}'_{2T}$	3	LL	$g_L^\perp$	$UU^{\cos\phi},\ LU^{\sin\phi}$	UU, LU	
$\mathbf{H}_{\mathbf{2T}} + \frac{\mathbf{t_o - t}}{\mathbf{4M^2}}\widetilde{\mathbf{H}}_{\mathbf{2T}}$	3	UT	$f_T^{(*)}, f_T^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU	
$\mathbf{H}'_{\mathbf{2T}} + \frac{\mathbf{t_o - t}}{\mathbf{4M^2}}\widetilde{\mathbf{H}}'_{\mathbf{2T}}$	3	LT	$g'_T, g_T^\perp$	$UU^{\cos\phi},UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU	
$\widetilde{\mathbf{E}}_{\mathbf{2T}} - \xi E_{2T}$	3	UL	$f_L^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT	Orbital angular momentum
$\widetilde{\mathbf{E}}'_{\mathbf{2T}} - \xi E'_{2T}$	3	LU	$g^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT	Spin Orbit
$\widetilde{\mathbf{H}}_{\mathbf{2T}}$	3	UT$_x$	$f_T^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT	Transverse Orbital angular momentum
$\widetilde{\mathbf{H}}'_{\mathbf{2T}}$	3	LT$_x$	$g_T^\perp$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT	

Newly accessible configurations!

We can access all twist three GPDs and test the unique information in their qgq structure, e.g. OAM GPD
M. Engelhardt' talk

Straight link

$$\tilde{E}_{2T} = -\int_x^1 \frac{dy}{y}(H+E) + \left[\frac{\tilde{H}}{x} - \int_x^1 \frac{dy}{y^2}\tilde{H}\right] + \left[\frac{1}{x}\mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2}\mathcal{M}_{F_{14}}\right]$$

WW term

genuine twist three term

Staple link

$$\tilde{E}_{2T} = -\int_x^1 \frac{dy}{y}(H+E) + \left[\frac{\tilde{H}}{x} - \int_x^1 \frac{dy}{y^2}\tilde{H}\right] + \left[\frac{1}{x}\mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2}\mathcal{M}_{F_{14}}\right] -$$

$$\int_x^1 \frac{dy}{y}\mathcal{A}_{F_{14}}$$

from the staple

An experimental measurement of twist 3 GPDs from DVCS only is sensitive to OAM but it cannot disentangle the difference between JM and Ji decompositions

BH

$$\frac{d^5\sigma_{BH}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \Gamma\left|T_{BH}\right|^2 = \frac{\Gamma}{t}\left\{F_{UU}^{BH} + (2\Lambda)(2h)F_{LL}^{BH} + (2\Lambda_T)(2h)F_{LT}^{BH}\right\}$$

$$\frac{d^5\sigma_{unpol}^{BH}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} \equiv \frac{\Gamma}{t}F_{UU}^{BH} = \frac{\Gamma}{t}\left[\boxed{A(y, x_{Bj}, t, Q^2, \phi)}\left(F_1^2 + \tau F_2^2\right) + \boxed{B(y, x_{Bj}, t, Q^2, \phi)}\tau G_M^2(t)\right]$$

$$A = \frac{16\,M^2}{t(k\,q')(k'\,q')}\left[4\tau\left((k\,P)^2 + (k'\,P)^2\right) - (\tau+1)\left((k\,\Delta)^2 + (k'\,\Delta)^2\right)\right]$$

$$B = \frac{32\,M^2}{t(k\,q')(k'\,q')}\left[(k\,\Delta)^2 + (k'\,\Delta)^2\right],$$

…compared to BKM, NPB (2001)

$$
|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{e^6}{x_{\mathrm{B}}^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \times \left\{ c_0^{\mathrm{BH}} + \sum_{n=1}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + s_1^{\mathrm{BH}} \sin(\phi) \right\},
$$

$$
\begin{aligned}
c_{0,\mathrm{unp}}^{\mathrm{BH}} = {}& 8K^2 \left\{ (2+3\epsilon^2)\frac{Q^2}{\Delta^2}\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) + 2x_{\mathrm{B}}^2 (F_1+F_2)^2 \right\} \\
&+ (2-y)^2 \left\{ (2+\epsilon^2)\left[\frac{4x_{\mathrm{B}}^2 M^2}{\Delta^2}\left(1+\frac{\Delta^2}{Q^2}\right)^2 \right.\right. \\
&\qquad \left. + 4(1-x_{\mathrm{B}})\left(1 + x_{\mathrm{B}}\frac{\Delta^2}{Q^2}\right)\right]\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) \\
&\qquad + 4x_{\mathrm{B}}^2 \left[x_{\mathrm{B}} + \left(1 - x_{\mathrm{B}} + \frac{\epsilon^2}{2}\right)\left(1 - \frac{\Delta^2}{Q^2}\right)^2 \right. \\
&\qquad \left.\left. - x_{\mathrm{B}}(1-2x_{\mathrm{B}})\frac{\Delta^4}{Q^4}\right](F_1+F_2)^2 \right\} \\
&+ 8(1+\epsilon^2)\left(1 - y - \frac{\epsilon^2 y^2}{4}\right) \\
&\times \left\{ 2\epsilon^2 \left(1 - \frac{\Delta^2}{4M^2}\right)\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) - x_{\mathrm{B}}^2\left(1 - \frac{\Delta^2}{Q^2}\right)^2 (F_1+F_2)^2 \right\},
\end{aligned}
$$

$$
\begin{aligned}
c_{1,\mathrm{unp}}^{\mathrm{BH}} = {}& 8K(2-y)\left\{ \left(\frac{4x_{\mathrm{B}}^2 M^2}{\Delta^2} - 2x_{\mathrm{B}} - \epsilon^2 \right)\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) \right. \\
&\left. + 2x_{\mathrm{B}}^2 \left(1 - (1-2x_{\mathrm{B}})\frac{\Delta^2}{Q^2}\right)(F_1+F_2)^2 \right\},
\end{aligned}
$$

$$
c_{2,\mathrm{unp}}^{\mathrm{BH}} = 8x_{\mathrm{B}}^2 K^2 \left\{ \frac{4M^2}{\Delta^2}\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) + 2(F_1+F_2)^2 \right\}.
$$

BH-DVCS interference

$$\frac{d^5\sigma_{\mathcal{I}}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = e_l\Gamma\left(T^*_{BH}T_{DVCS} + T^*_{DVCS}T_{BH}\right)$$
$$= e_l\,\frac{\Gamma}{Q^2\mid t\mid}\left\{F^{\mathcal{I}}_{UU} + (2h)F^{\mathcal{I}}_{LU} + (2\Lambda)F^{\mathcal{I}}_{UL} + (2h)(2\Lambda)F^{\mathcal{I}}_{LL} + (2\Lambda_T)F^{\mathcal{I}}_{UT} + (2h)(2\Lambda_T)F^{\mathcal{I}}_{LT}\right\}$$

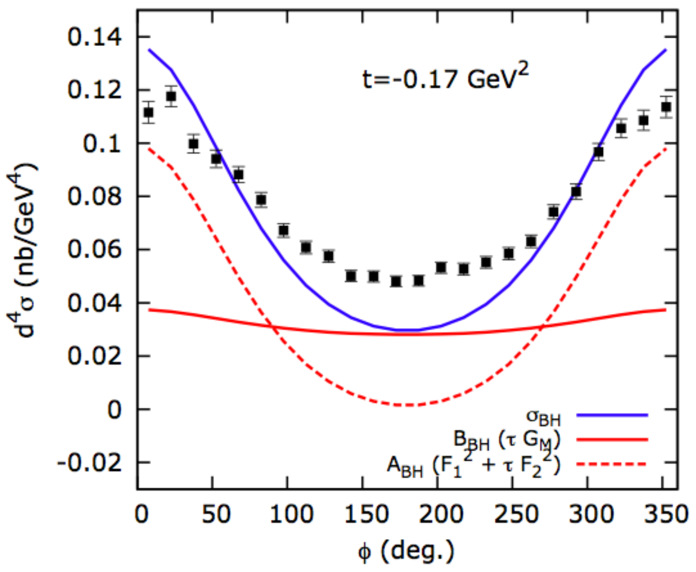
Unpolarized

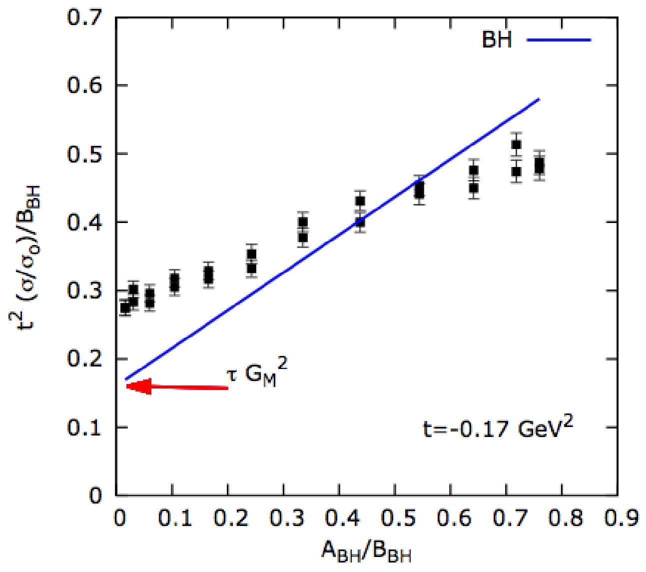
$$F^{\mathcal{I}}_{UU} = F^{\mathcal{I},tw2}_{UU} + \frac{K}{\sqrt{Q^2}}F^{\mathcal{I},tw3}_{UU}$$

$$F^{\mathcal{I},tw2}_{UU} = A^{\mathcal{I}}_{UU}\,\Re e\left(F_1\mathcal{H} + \tau F_2\mathcal{E}\right) + B^{\mathcal{I}}_{UU}G_M\,\Re e\left(\mathcal{H}+\mathcal{E}\right) + C^{\mathcal{I}}_{UU}G_M\,\Re e\widetilde{\mathcal{H}}$$

$$F^{\mathcal{I},tw3}_{UU} = \Re e\Big\{A^{(3)\mathcal{I}}_{UU}\left[F_1(2\widetilde{\mathcal{H}}_{2T} + \mathcal{E}_{2T}) + F_2(\mathcal{H}_{2T} + \tau\widetilde{\mathcal{H}}_{2T})\right]$$
$$+B^{(3)\mathcal{I}}_{UU}G_M\,\widetilde{E}_{2T} + C^{(3)\mathcal{I}}_{UU}G_M\left[2\xi H_{2T} - \tau(\widetilde{E}_{2T} - \xi E_{2T})\right]\Big\}$$

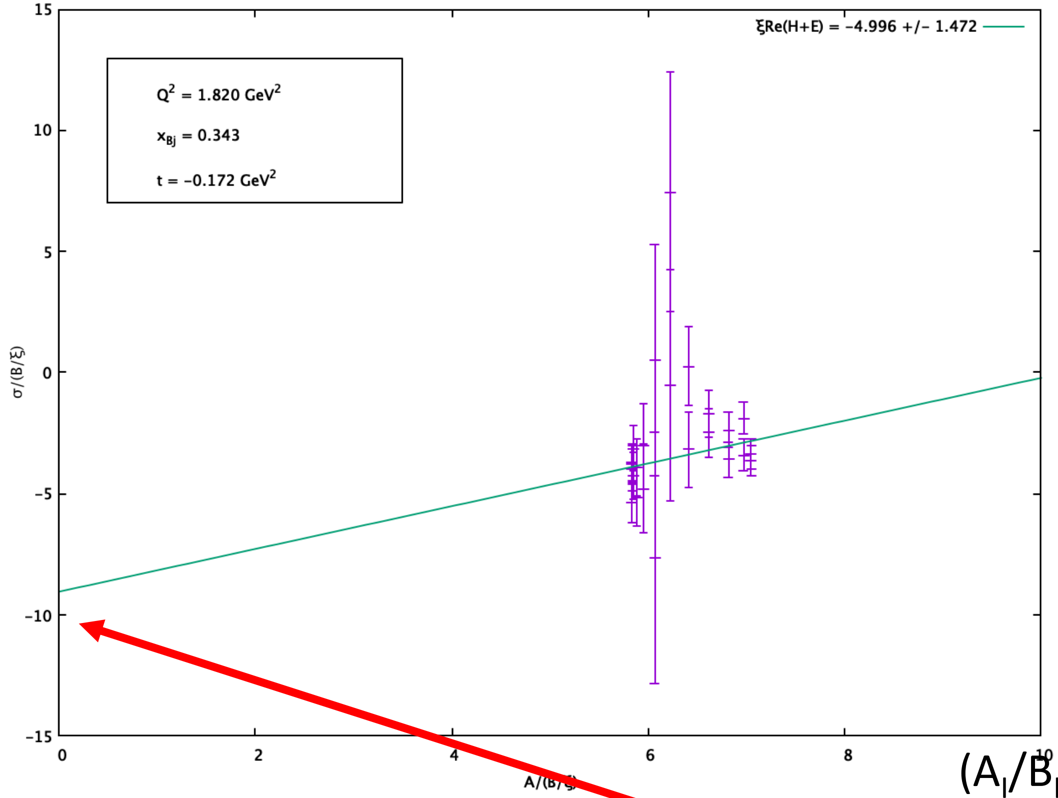
Rosenbluth separation for Bethe-Heitler contribution





$$\frac{d^5\sigma^{BH}_{unpol}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\Gamma}{t^2}\left[A_{BH}\boxed{(F_1^2+\tau F_2^2)} + B_{BH}\boxed{\tau G_M^2(t)}\right]$$

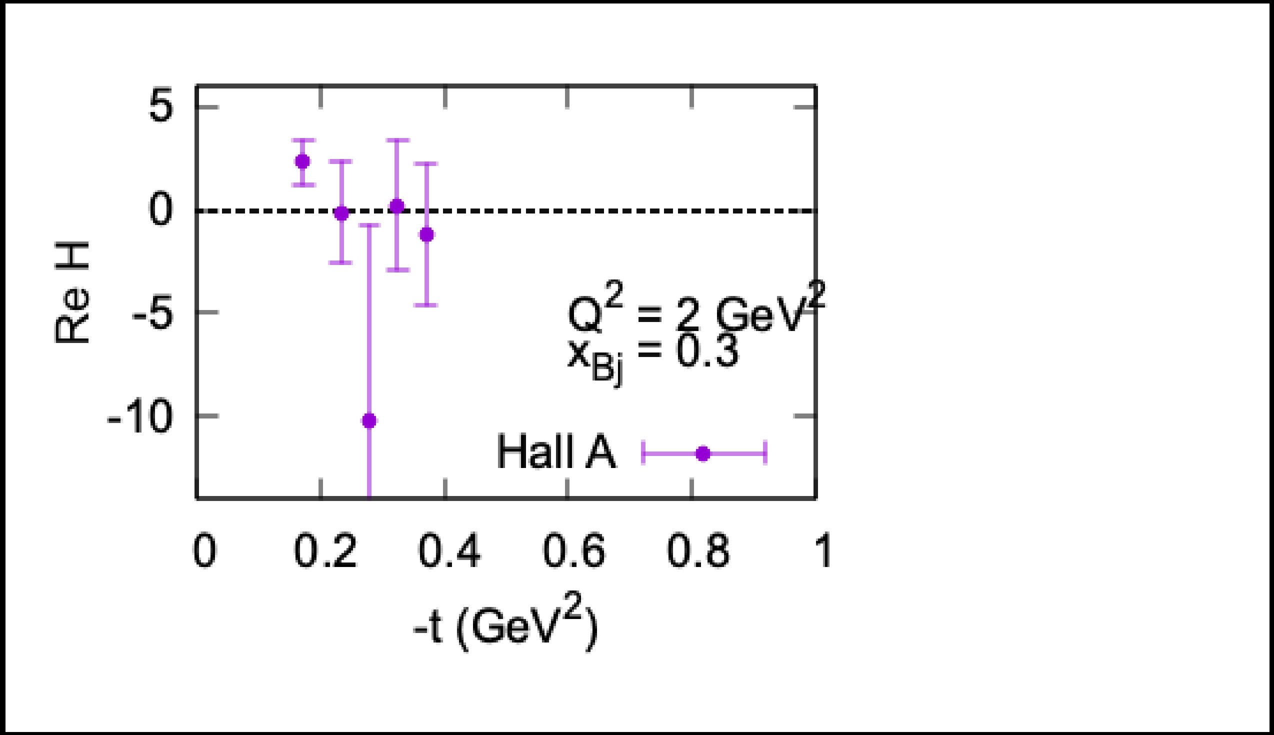
Rosenbluth Separated Data for BH-DVCS



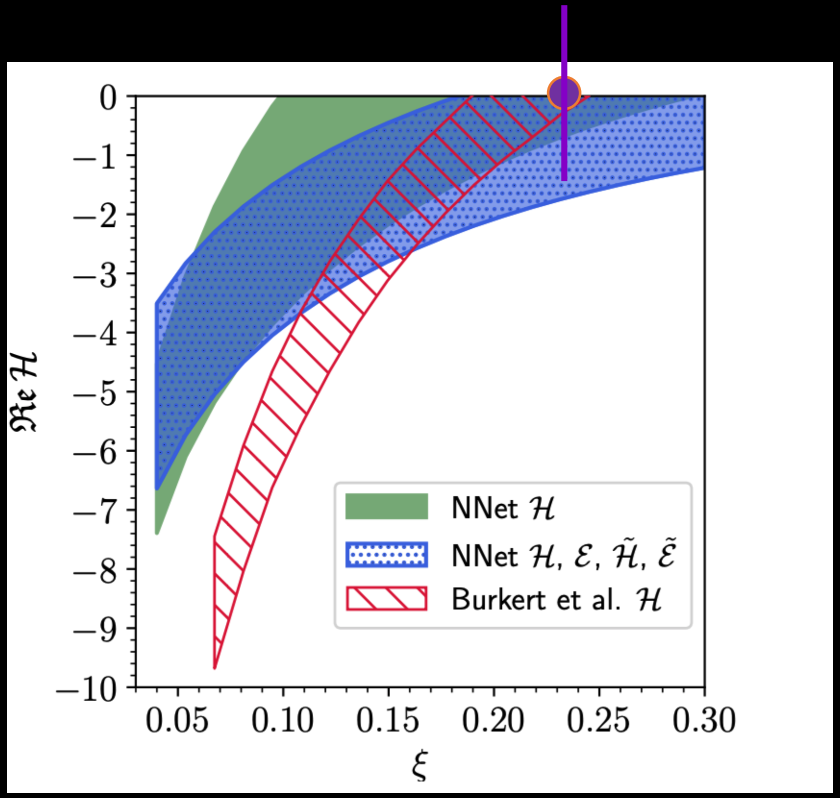
(A_I/B_I)

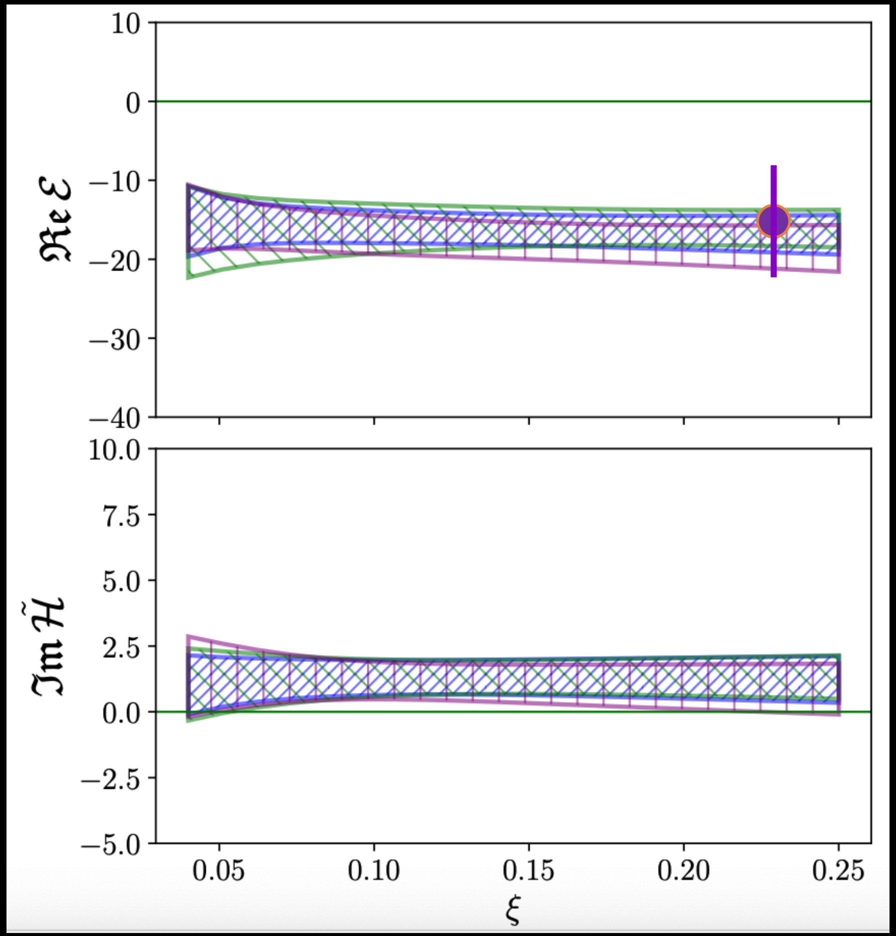
Hall A data, Defurne

$$\frac{d^5\sigma^{\mathcal{I}}_{unpol}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\Gamma}{Q^2(-t)}\left[A_{\mathcal{I}}\overset{G_E^2+\tau G_M^2}{\boxed{(F_1\Re e\mathcal{H}+\tau F_2\Re e\mathcal{E})}} + B_{\mathcal{I}}\overset{G_M^2}{\boxed{G_M\,\Re e(\mathcal{H}+\mathcal{E})}} + C_{\mathcal{I}}\overset{G_M\,G_A}{\boxed{G_M\,\Re e\widetilde{\mathcal{H}}}}\right]$$


5
0
-5
-10
Re H
0
0.2
0.4
0.6
0.8
1
-t (GeV^2)
Q^2 = 2 GeV^2
x_{Bj} = 0.3
Hall A

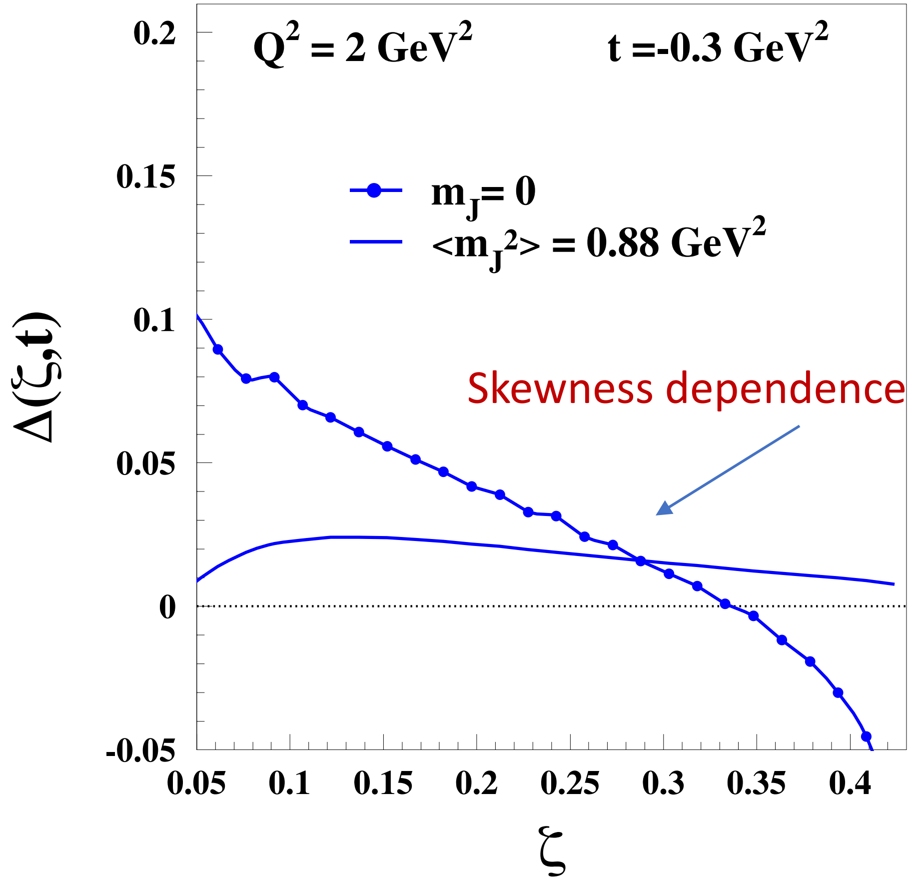
Comparison with other/BKM based analyses





Impact on pressure extraction through dispersion relations

$$\mathrm{Re}\,\mathcal{H}^{(\pm)}(\xi,t) = \frac{1}{\pi}\Big[P.V.\int_{-1}^{\xi_{\mathrm{th}}} dx\,\frac{H^{(\pm)}(x,x,t)}{x-\xi} + \int_{\xi_{\mathrm{th}}}^{+1} dx\,\frac{H^{(\pm)}_{\mathrm{unphys}}(x,x,t)}{x-\xi}\Big],$$



Skewness dependence induced by finite threshold effects

Phys.Rev. D80 (2009) 071501

Center for Nuclear Femtography Project at Jefferson Lab

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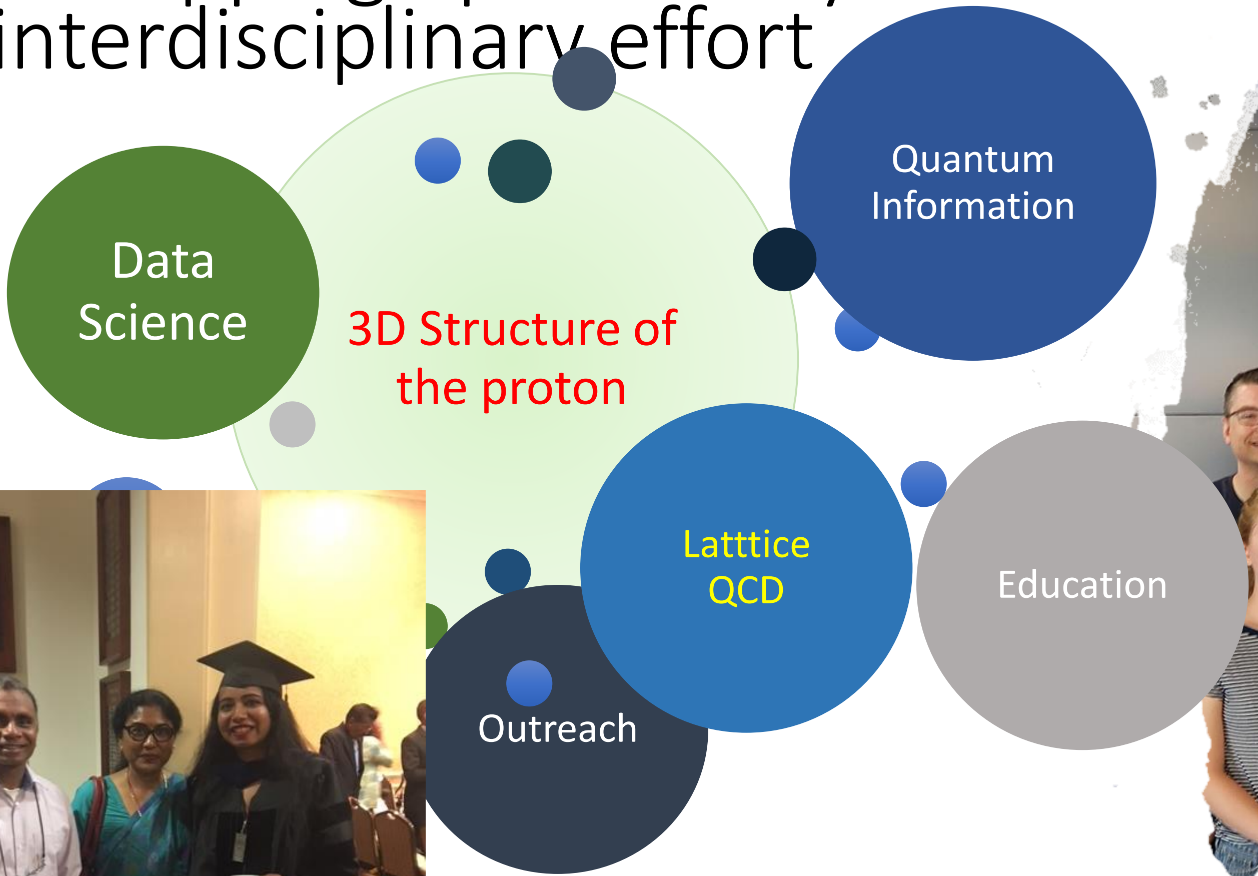
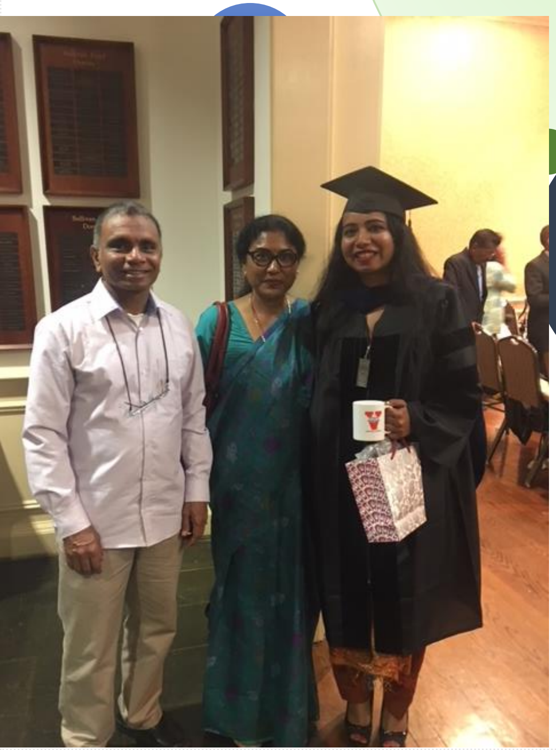
***

Red: Undergraduate
Blue: Graduate

The University of Virginia is stepping up this truly interdisciplinary effort

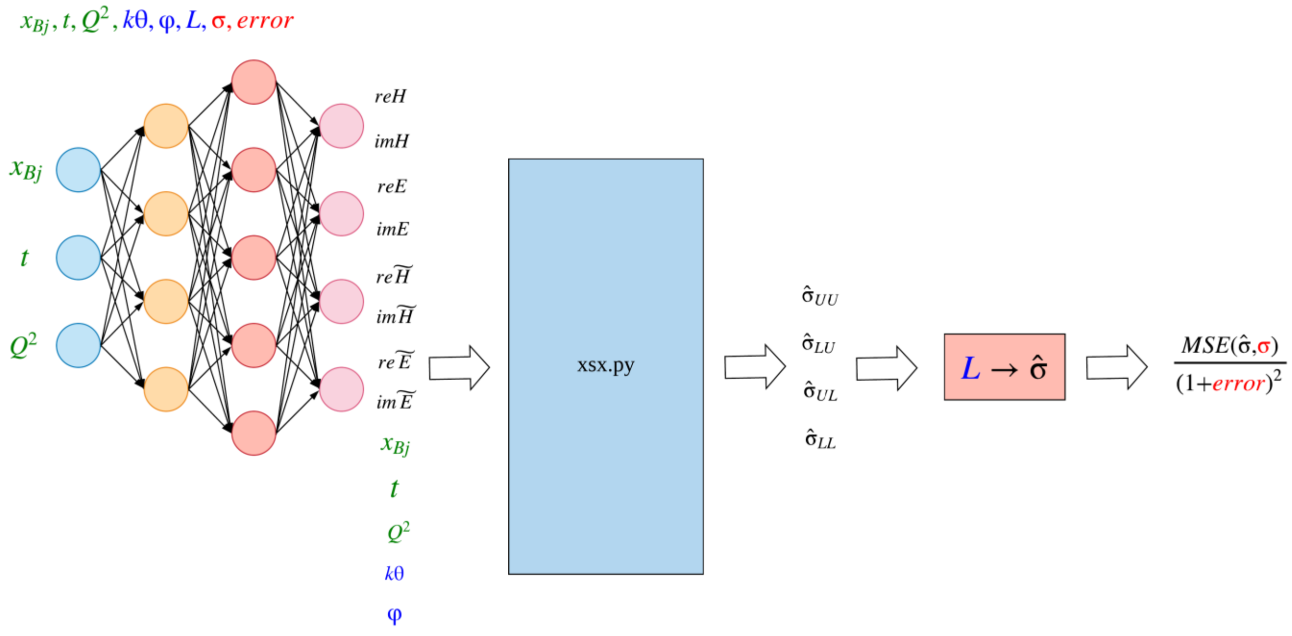




Femtography Imaging with Neural Networks (FINN)

Strategy:

1. A fully connected neural network maps input kinematic data to a vector of eight form factors (see diagram).
2. Use a code developed by our Data Analysis Team to evaluate the cross sections and in terms of the CFFs.



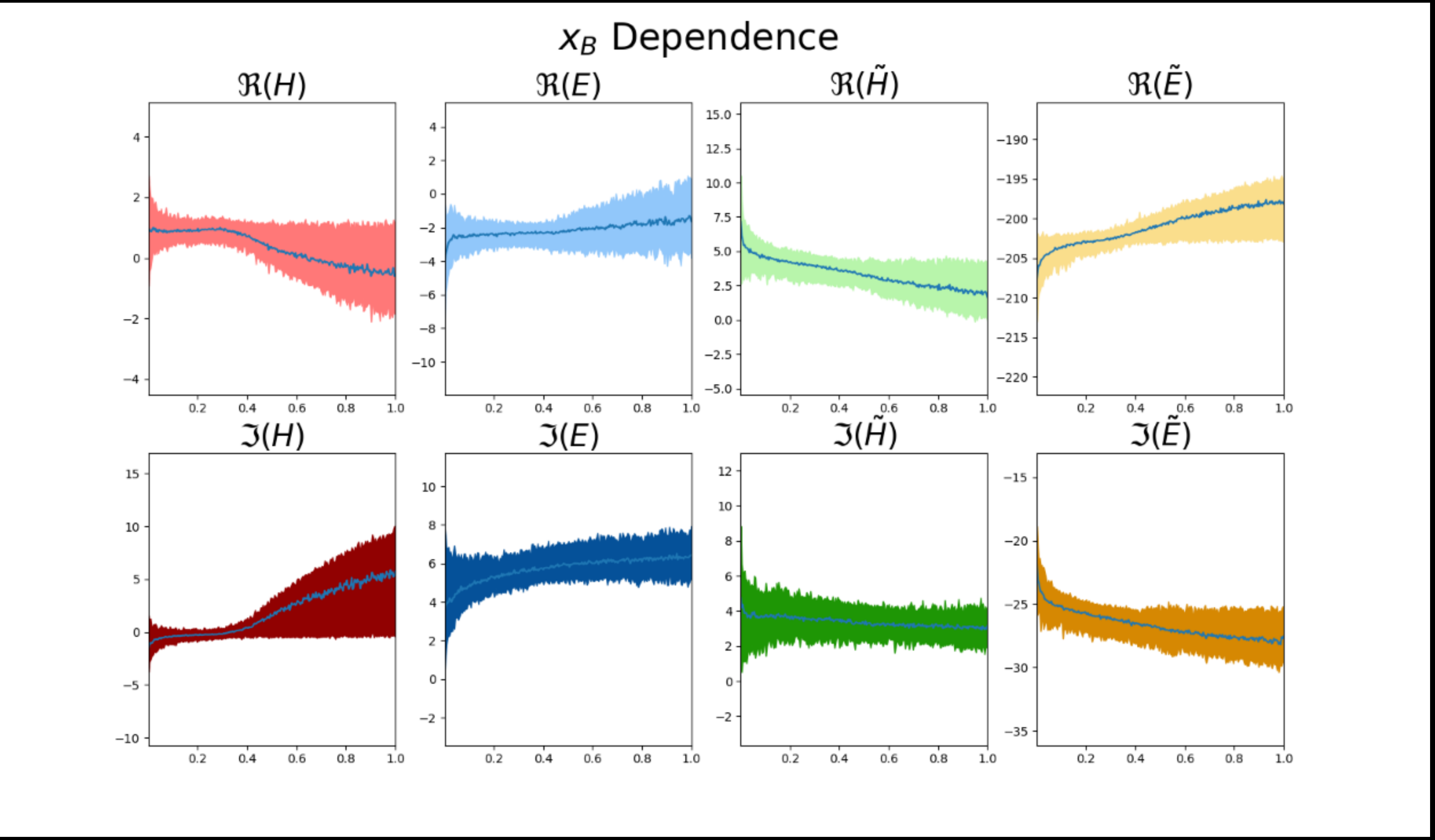
Jake Grigsby

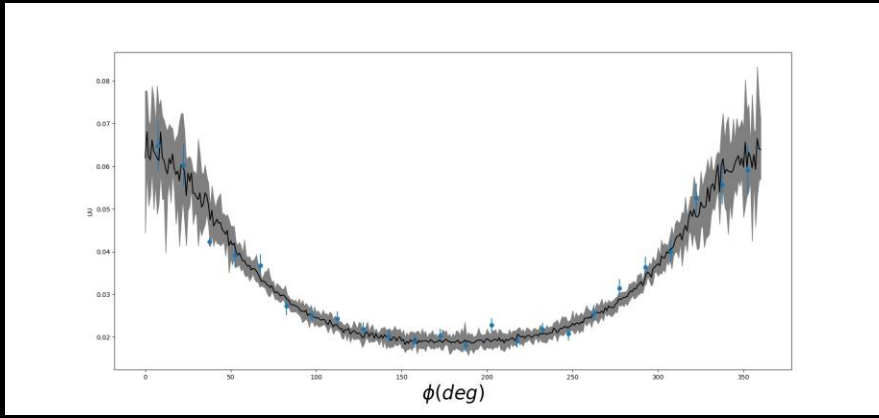
We translate the x-sec. code into TensorFlow

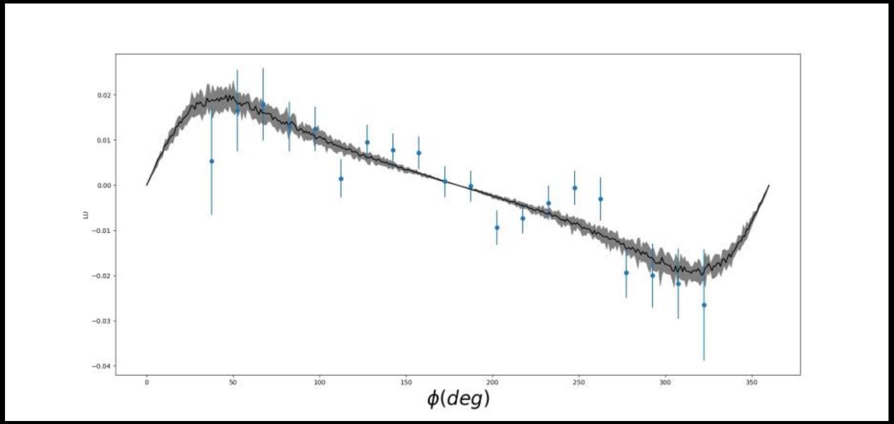
➔Automatically differentiable

➔At variance with other efforts we can train CFF extraction network with backpropagation and variants of stochastic gradient descent.

Compton Form factors







Conclusions and Outlook

- The EoS of dense matter in QCD can be obtained from first principles, using **ab initio calculations for both quark and gluon d.o.f.**

- **Gluons** are found to dominate the EoS providing a trend in the high density regime which is consistent with the constraint from LIGO.

These effects are observable!

- We can connect the **pressure and energy density** in neutron stars with collider observables: the **GPDs.**

- The proposed line of research opens up a new framework for understanding the properties of **hybrid stars**. In the future we hope to set more stringent constraints on the nature of the **hadron to quark matter transition** at zero temperature.

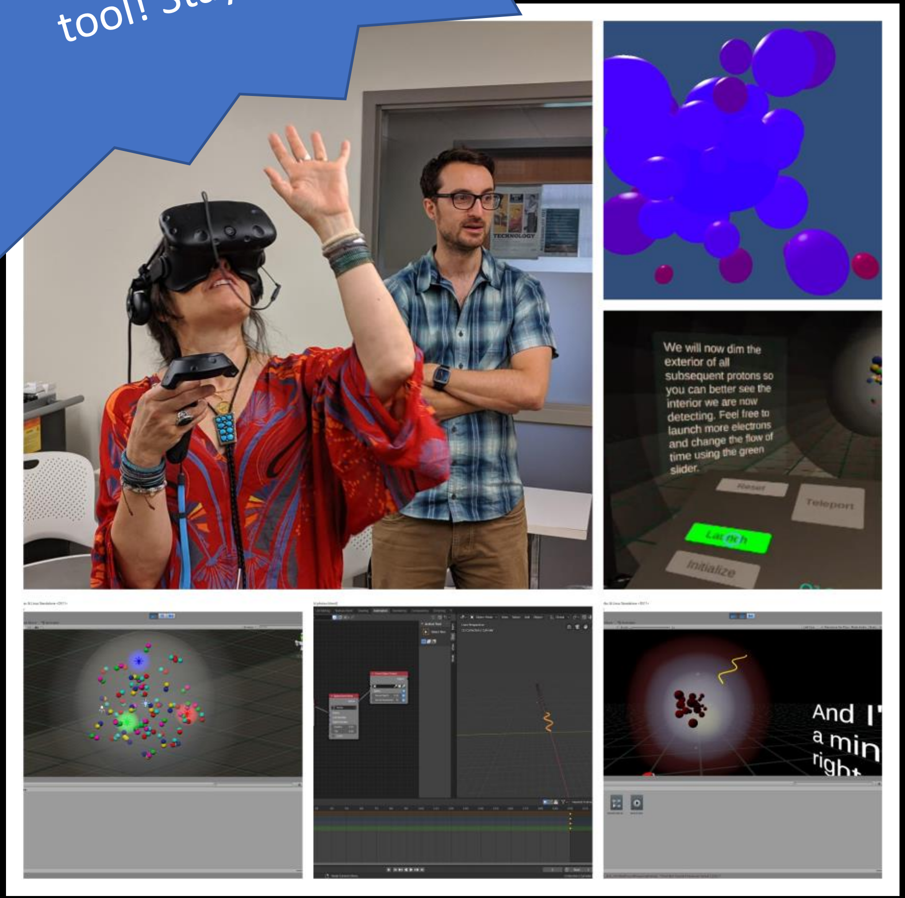
- Jefferson Lab's measurement on the pressure inside the nucleon/hadronic matter needs to be corroborated by an independent set of measurements

Neutron stars mergers/multimessenger astronomy provide an independent constraint

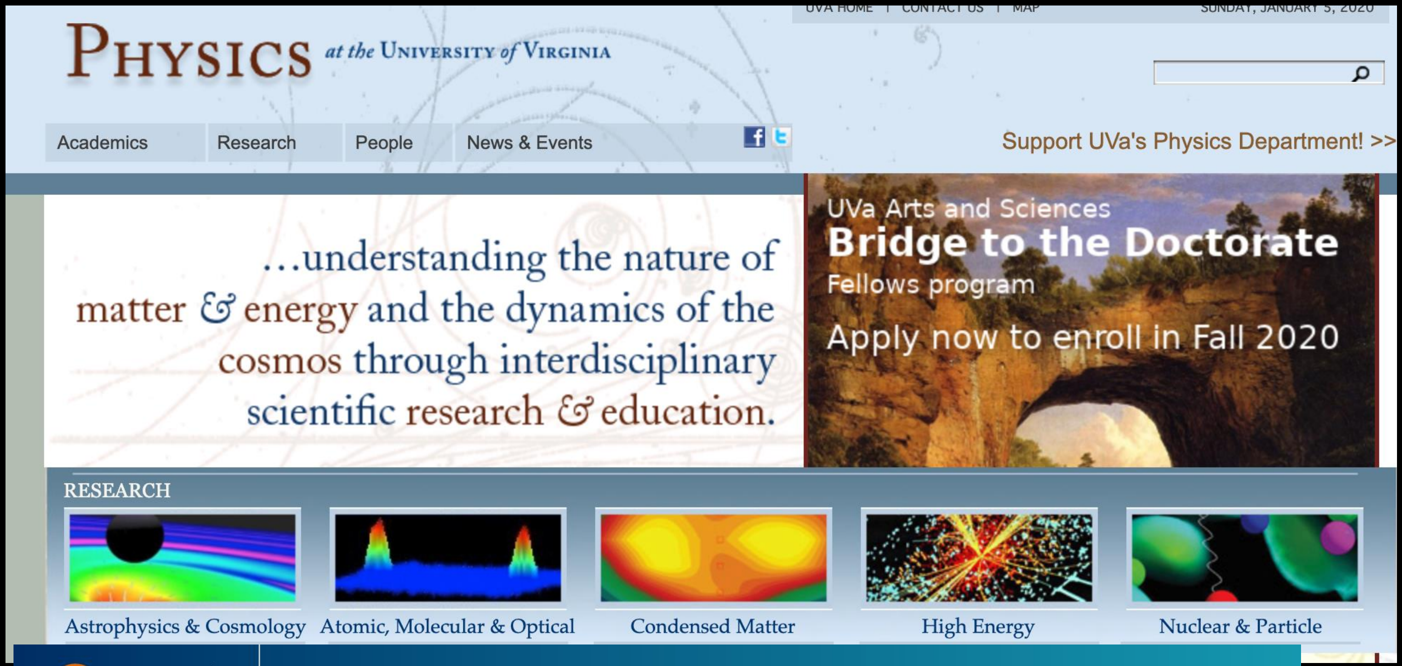
- To observe, evaluate and interpret Wigner distributions at the subatomic level requires stepping up data analyses from the standard methods ➔ developing new numerical/analytic/quantum computing methods

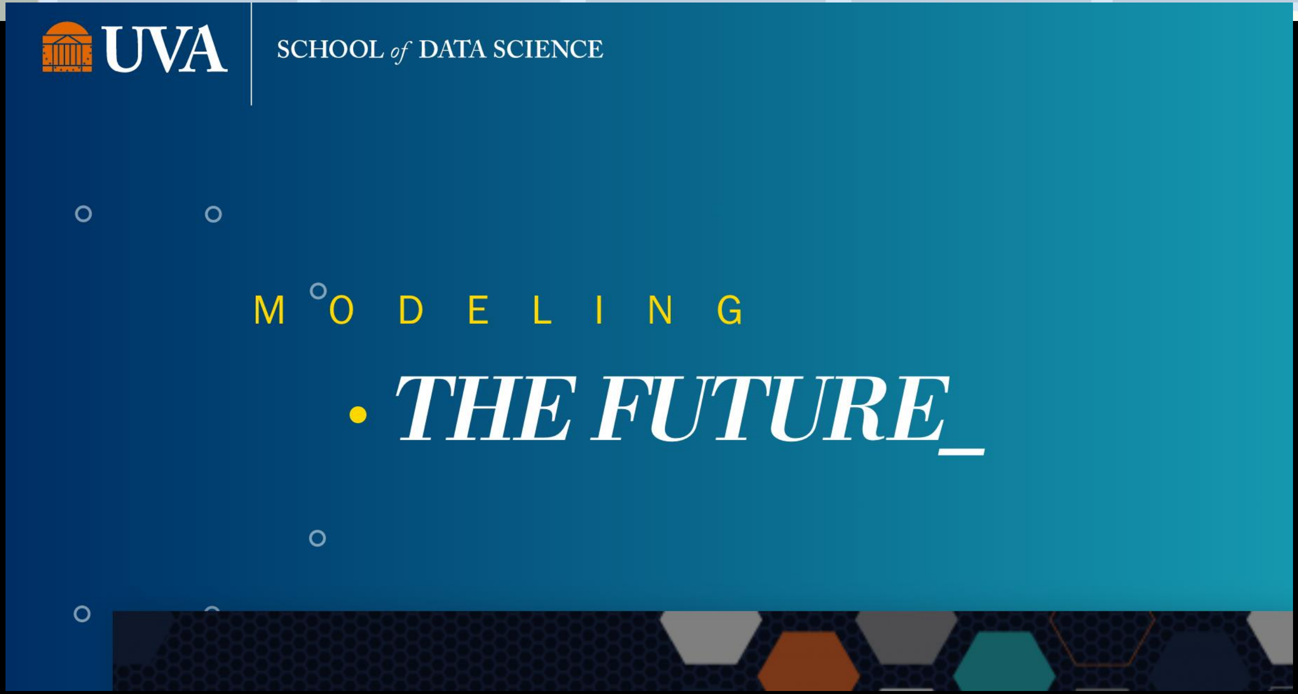
Center for Nuclear Femtography Project

We are releasing our VR tool! Stay tuned!



http://www.phys.virginia.edu/





1/6/2020